Relativistic heavy ion collisions

Constraining the symmetry energy at supra-normal densities

Yvonne Leifels

GSI, FOPI + ASYEOS

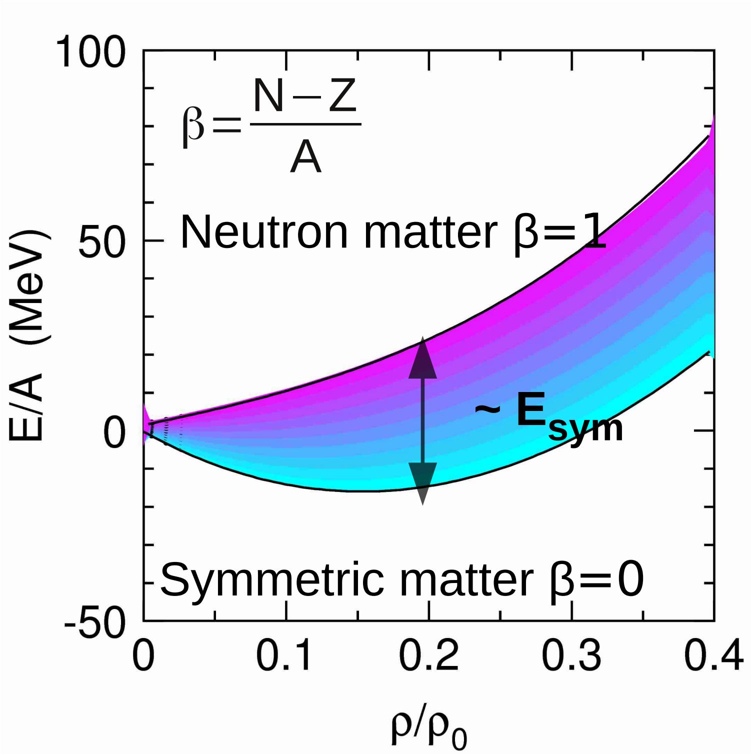
Outline

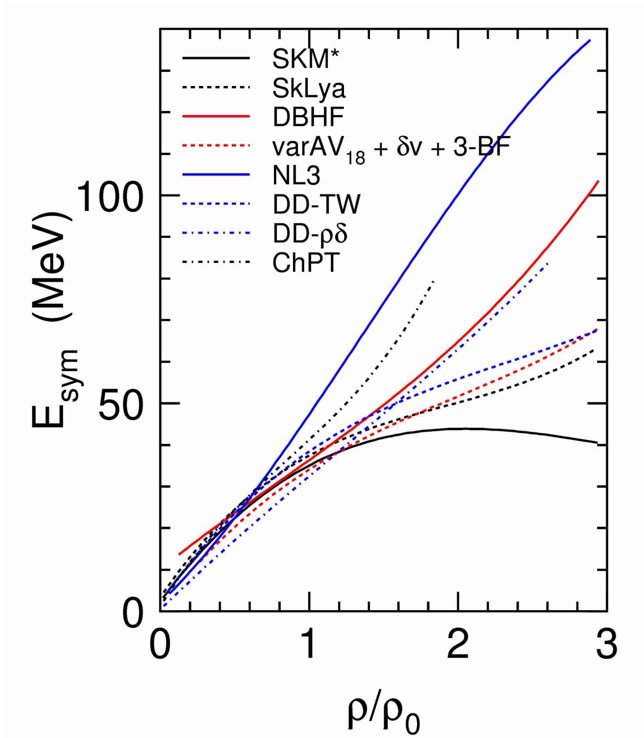
- Symmetry energy
- Heavy ion reactions at SIS/GSI
  - E > 400AMeV
- Summary and outlook

Symmetry energy

$E_{sym}(0)$ and slope parameter L

Fuchs and Wolter, EPJA 30 (2006)





L large
Stiff

L small
Soft

SE bending over
Super soft

Expansion
of the symmetry energy
at $\rho = \rho_0$

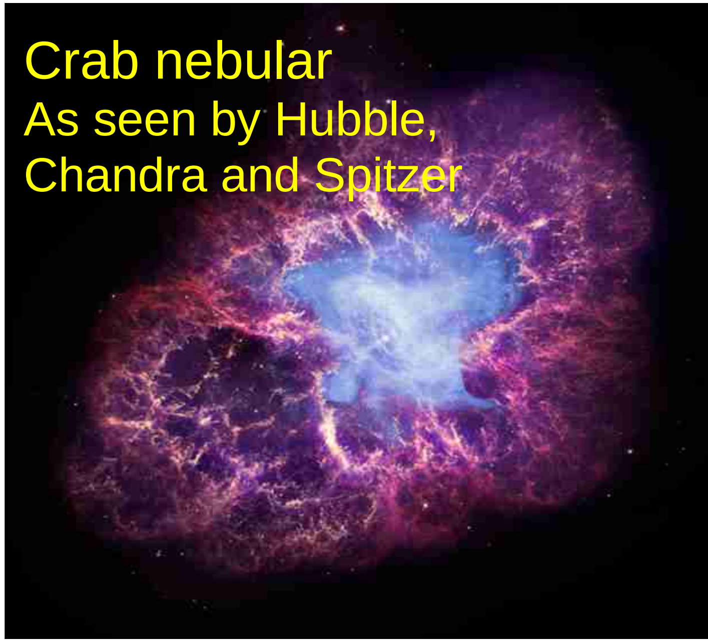
$$E_{sym}(\rho) = E_{sym,0} + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

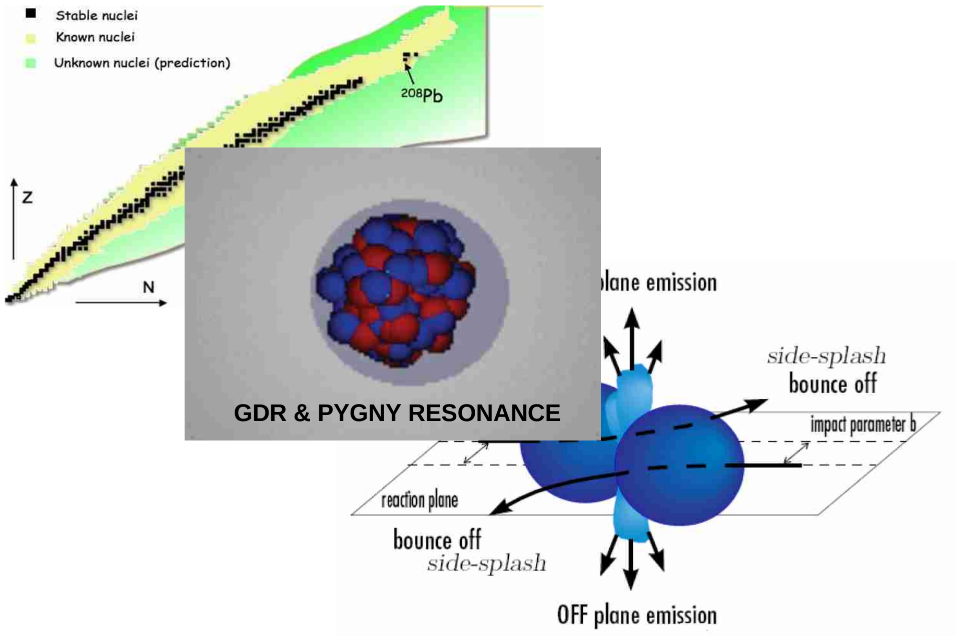
slope parameter $L = 3\rho_0 \left| \frac{dE_{sym}(\rho)}{d\rho} \right|_{\rho_0}$

Symmetry energy

Astrophysical relevance

- Proton fraction
- M-R relation
- Stability against gravitational collapse
- ρ_c for direct URCA
- Transition density
- Cooling rates



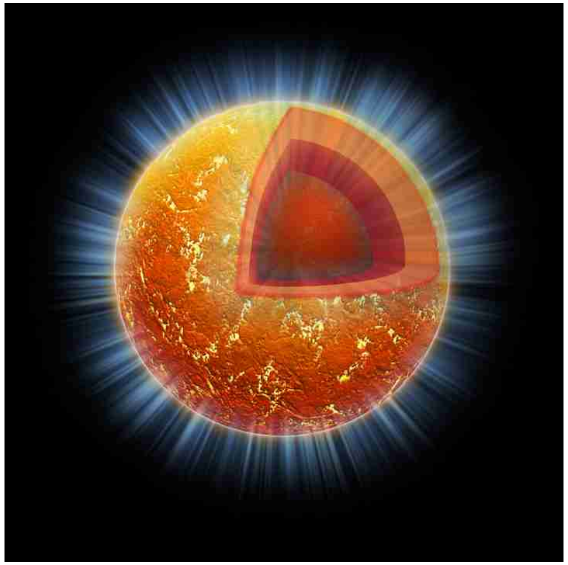


Nuclear structure and reactions ($\rho \approx \rho_0$)

- Masses → Fits to binding energies
- Neutron skins
- GDR & Pygmy resonances Correlations
- Yields of fragments
- Isoscaling, isospin diffusion
- Phase space distributions
- Particle production
- Flows ...

From HICs to compact stars

Equation of state of neutron matter



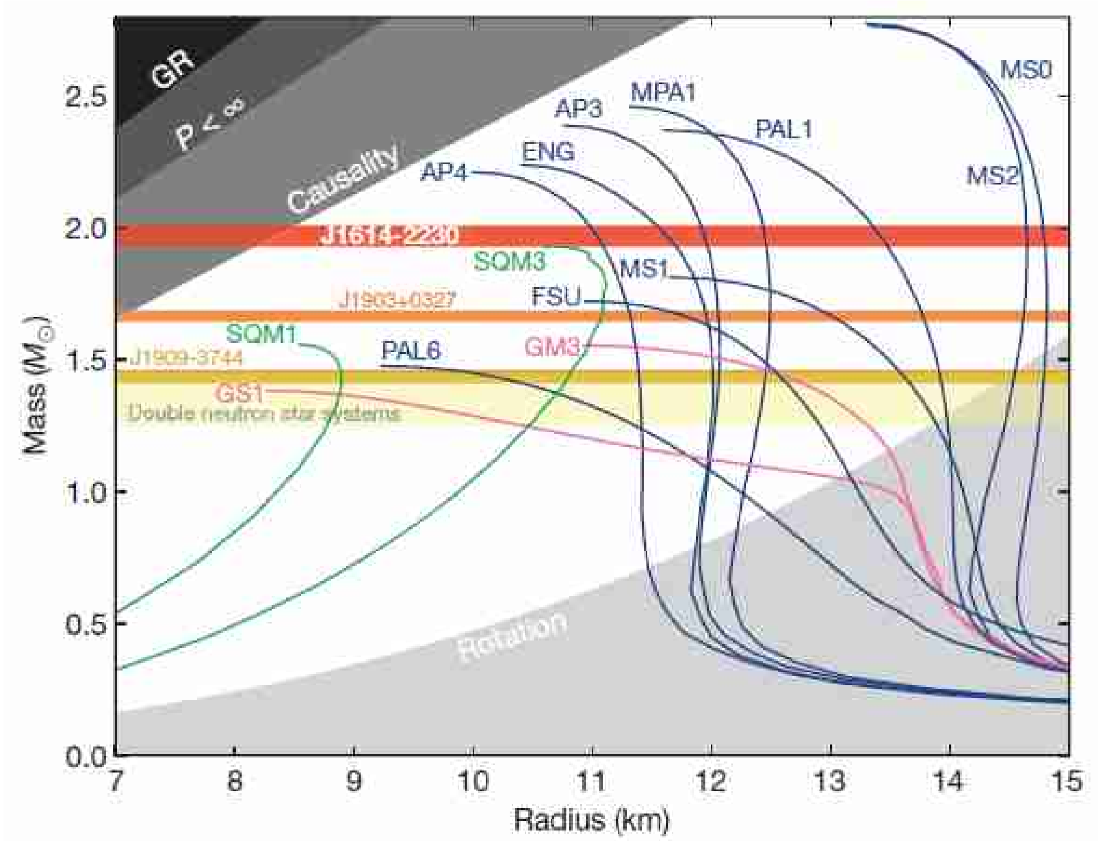
Interior of a neutron star

nucleons

nucleons + exotic

strangeness

Mass – Radius Relation



P.B. Demorest, Nature Oct. 2010

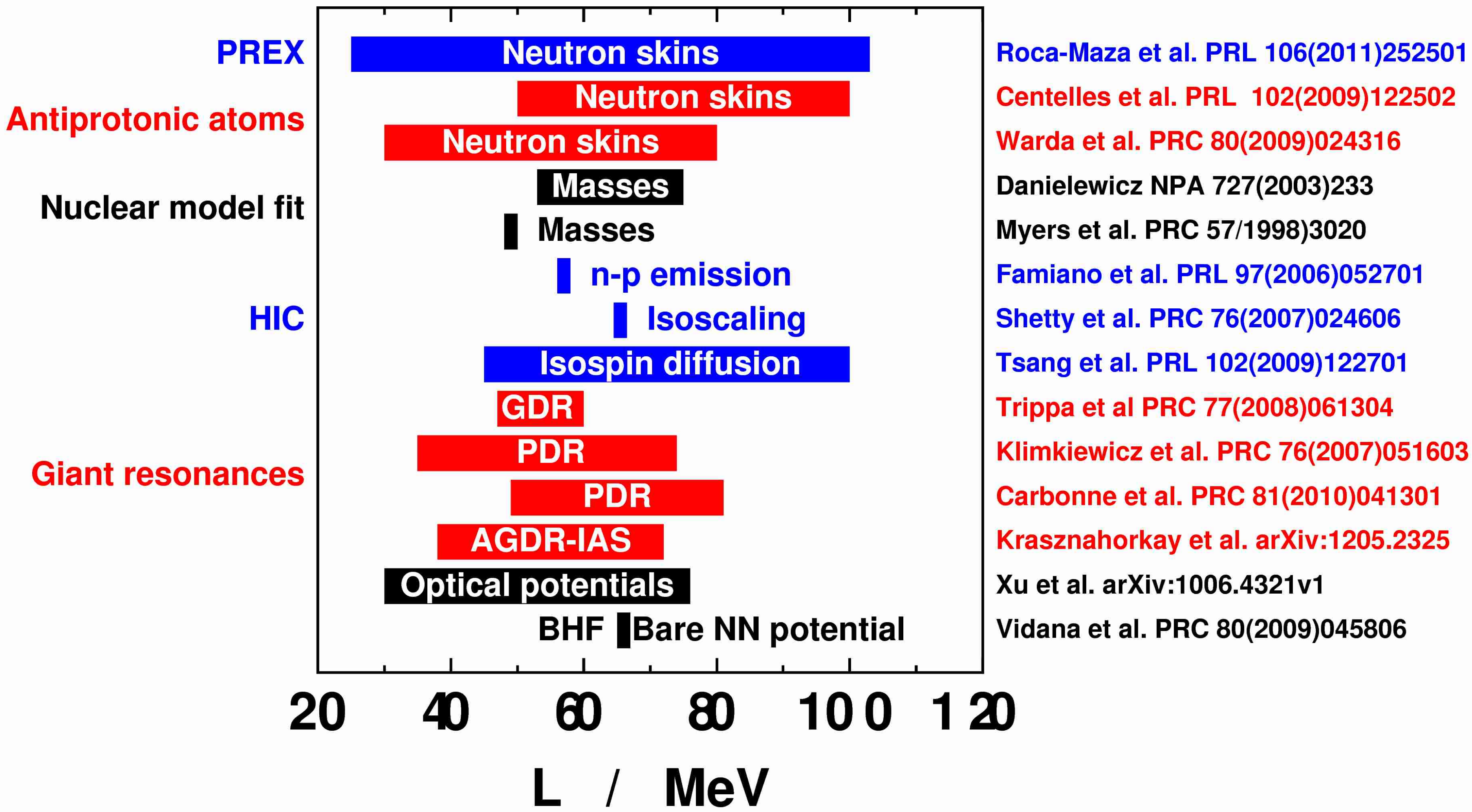
J1614-2230 binary system, Pulsar m = 1.97 +/- 0.04 M_{sun}

Direct mass measurement by Shapiro delay

Symmetry energy

At low and normal nuclear matter densities

Roca-Maza (2011)

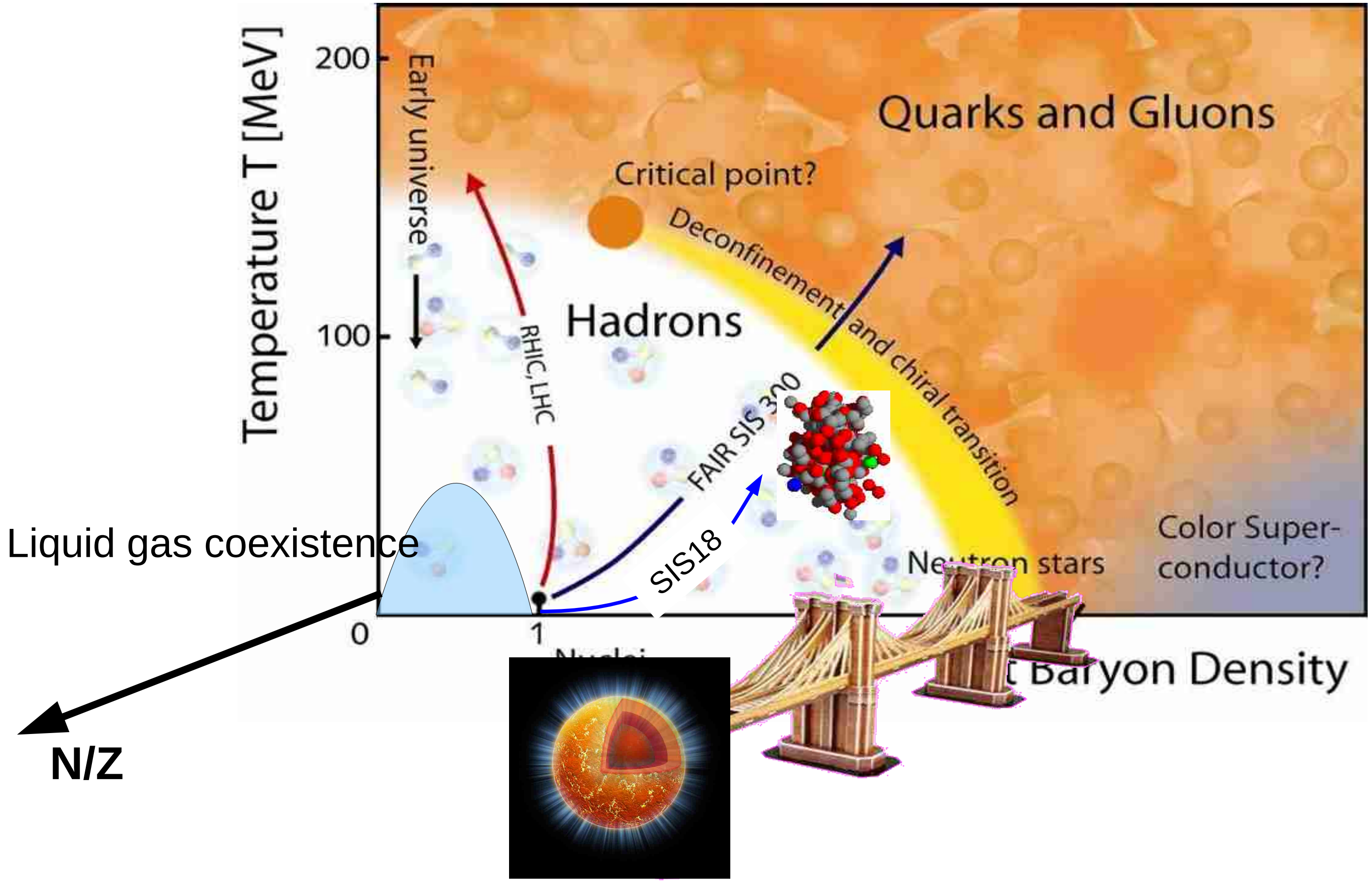


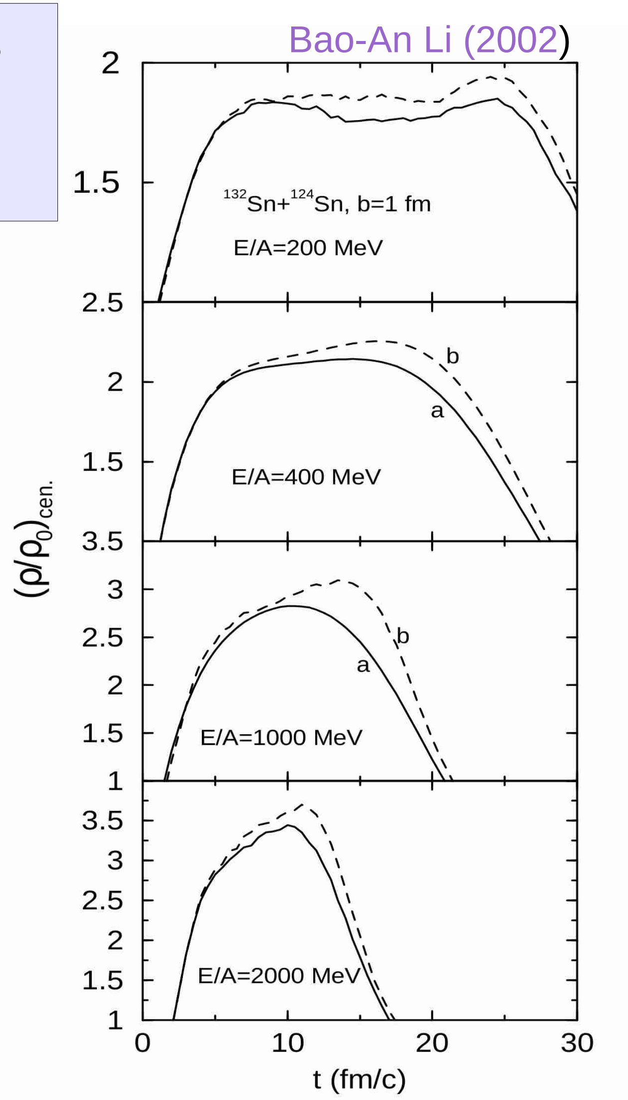
Heavy ion collisions at relativistic energies

Connecting nuclear experiments at low densities with neutron stars

→

bridging large range in nuclear matter density and N/Z





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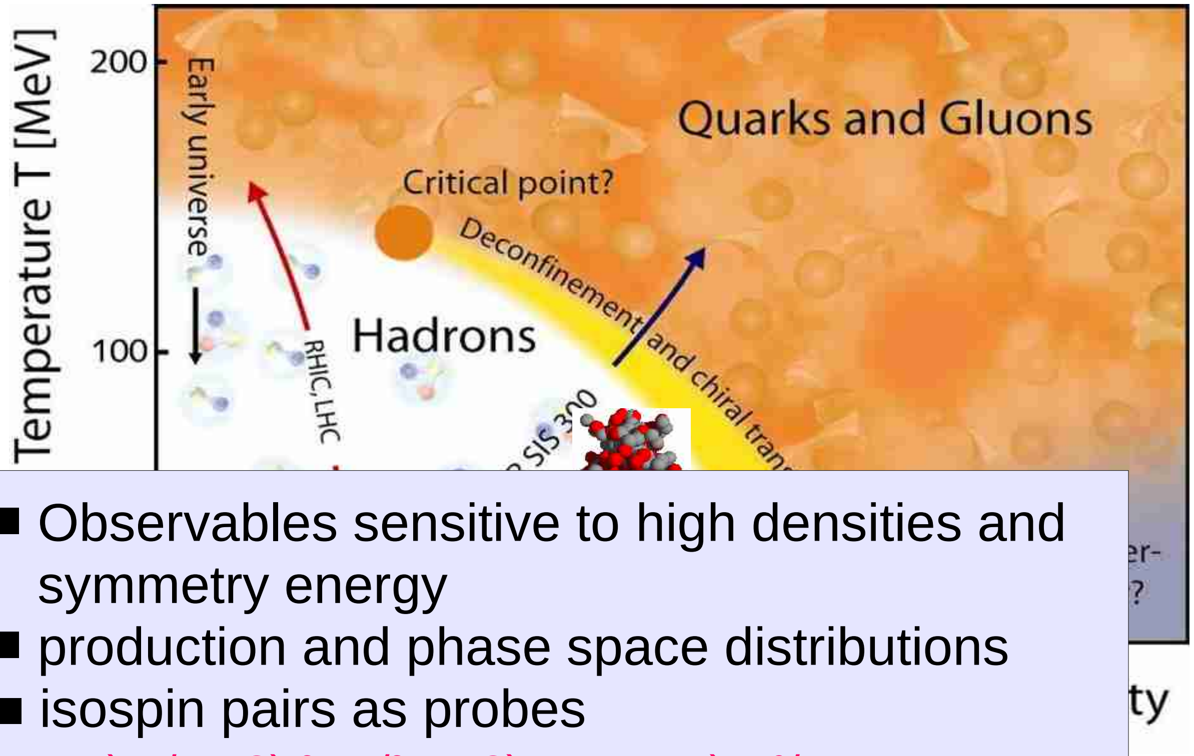
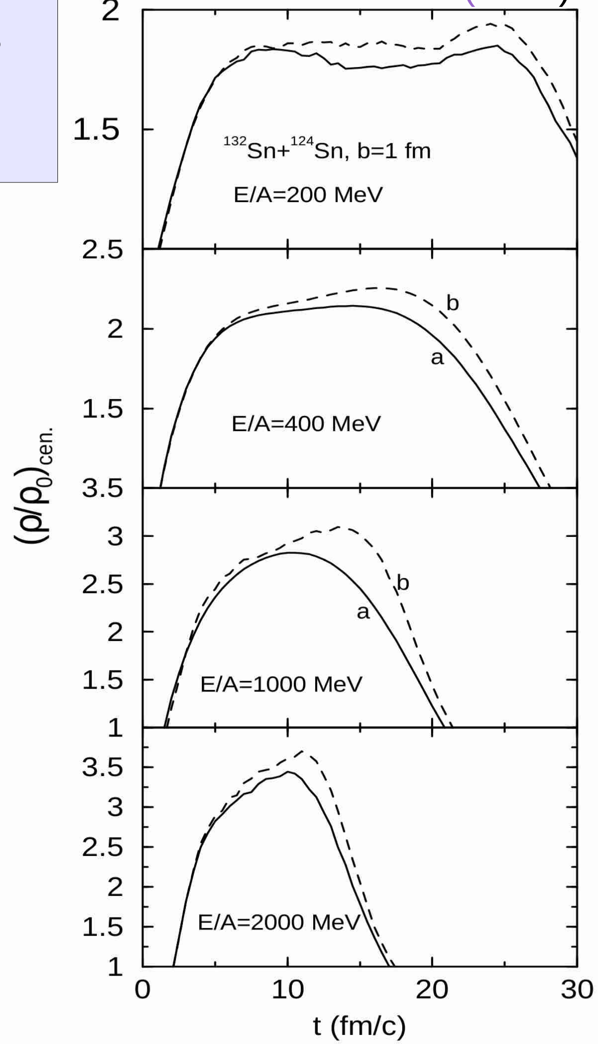


Liquid gas

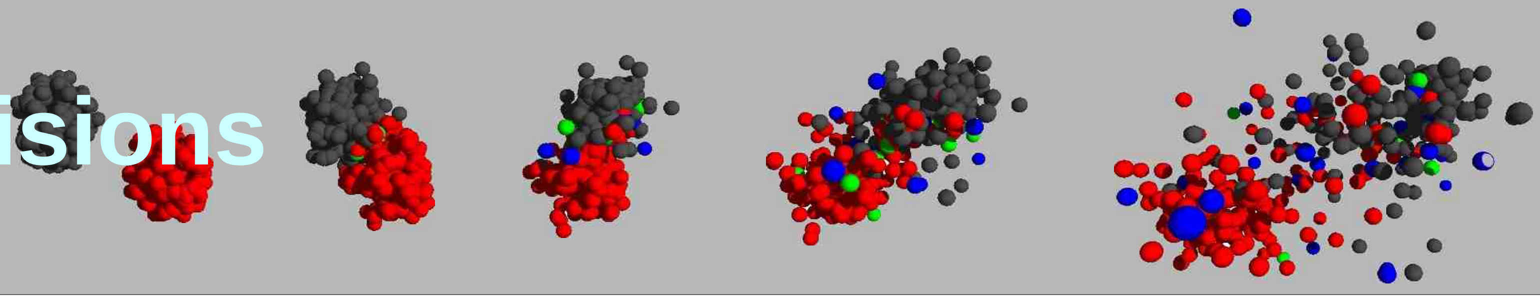
N/Z

- Observables sensitive to high densities and symmetry energy
- production and phase space distributions
- isospin pairs as probes
  1) n/p 2) $^3He/^3H$ 3) π^-/π^+ 4) K^0/K^+

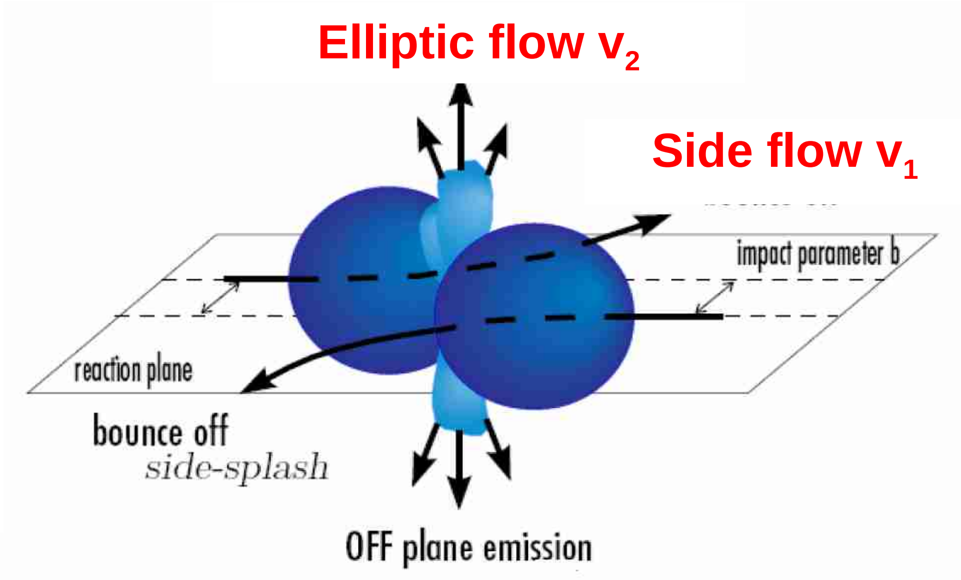
Bao-An Li (2002)

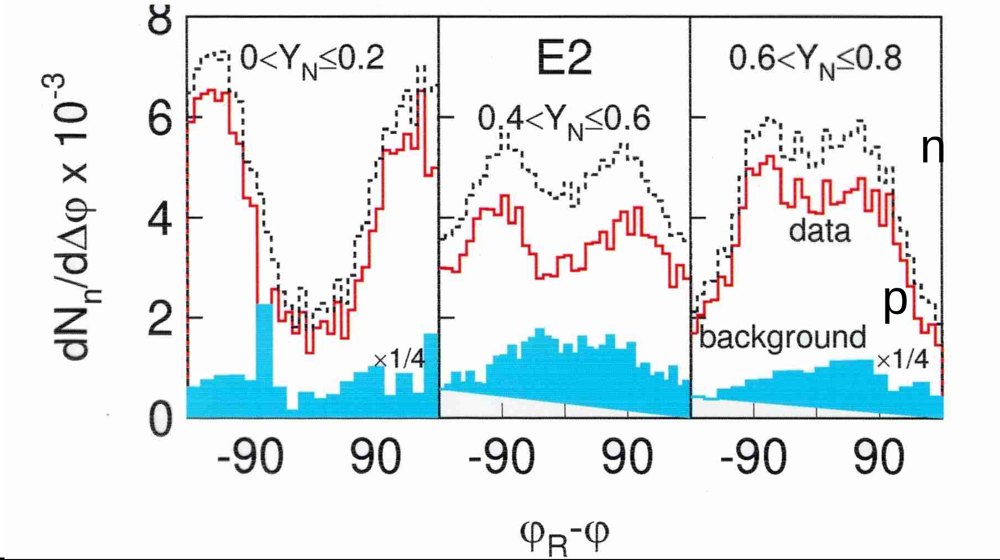


Heavy ion collisions



Intermediate densities – Flow of isospin pairs



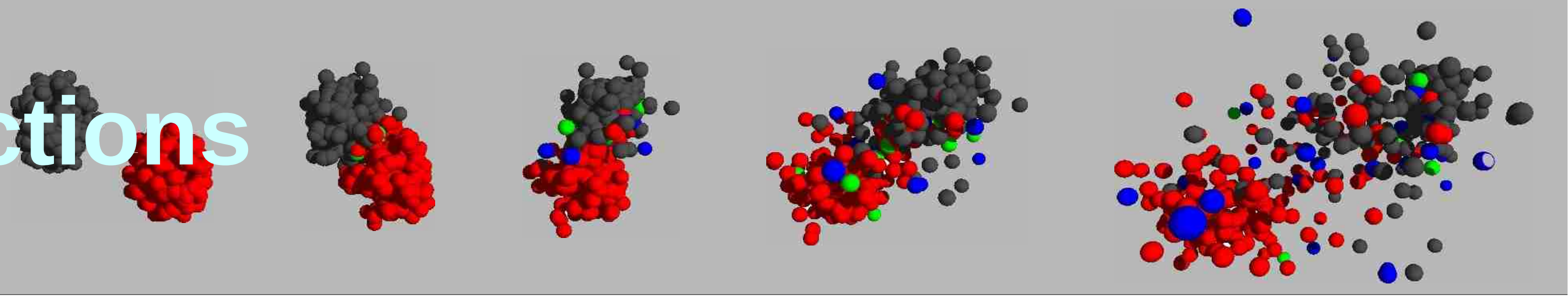


$$\frac{dN}{d\Phi} \propto 1 + 2v_1\cos(\Phi) + 2v_2\cos(2\Phi)$$

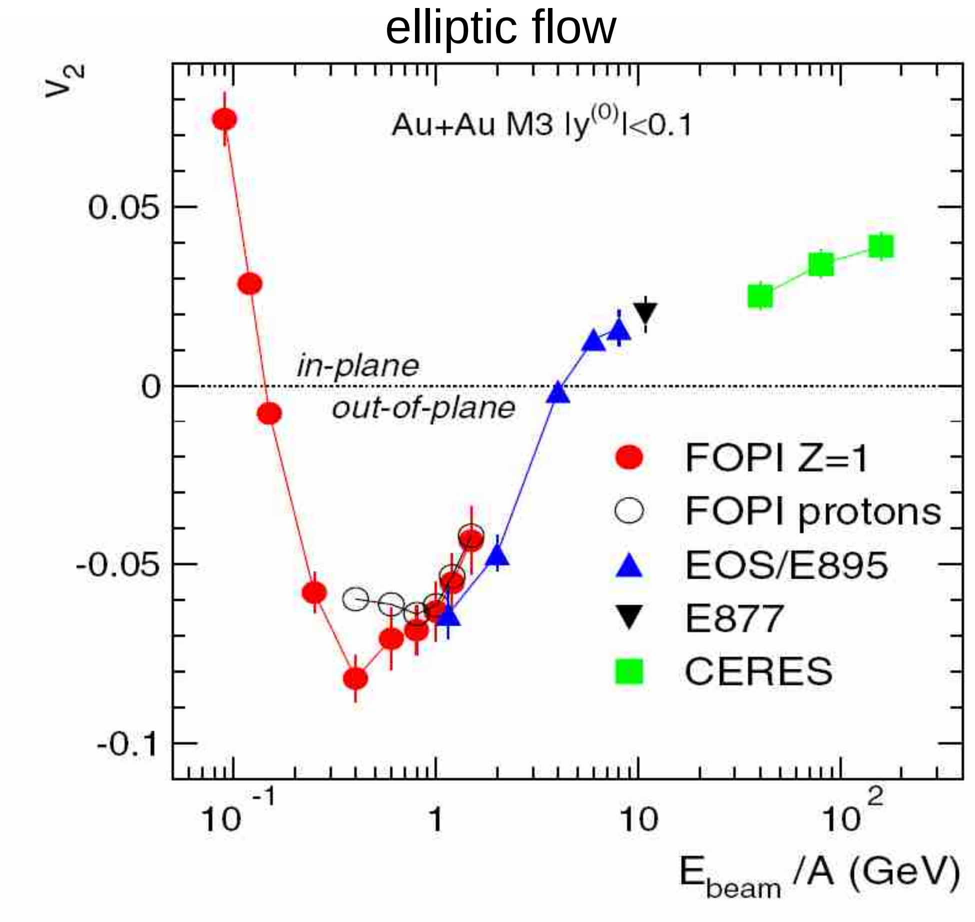
$$\Phi = \varphi_R - \varphi$$

- Sensitive to pressure changes
- Elliptic flow is a compression/expansion phenomenon
- Particles from the high density phase are emitted perpendicular to the reaction plane

Heavy ion reactions

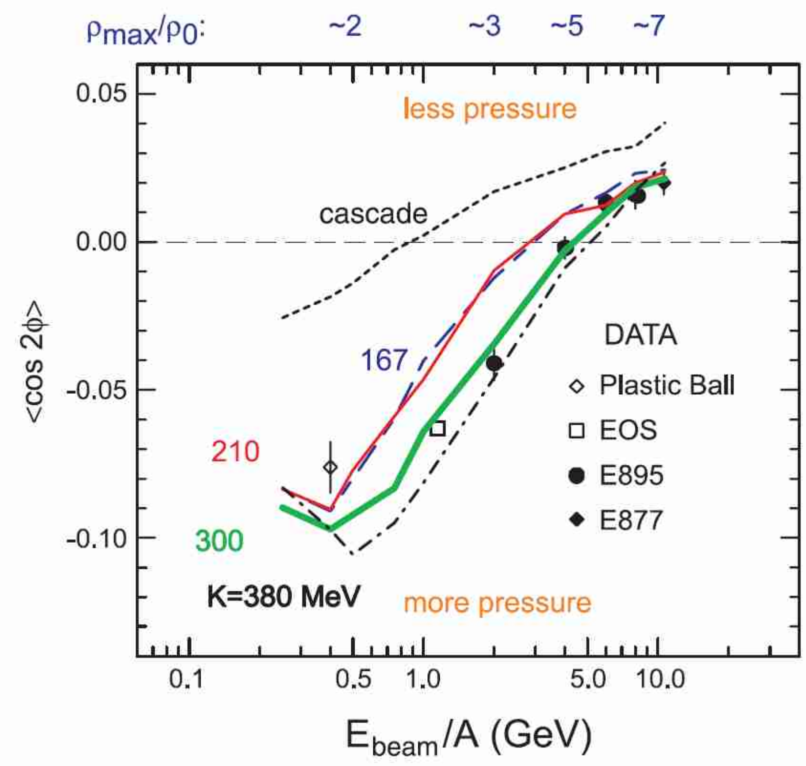


Excitation function of elliptic flow



H. Wessels et al. PR 15 (2002)

P. Danielewicz et al.
Science 298, 1592 (2002)



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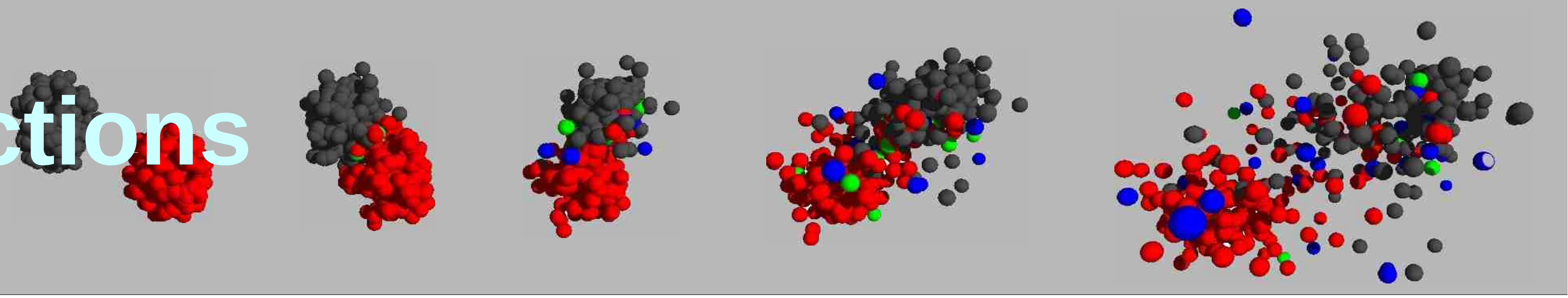

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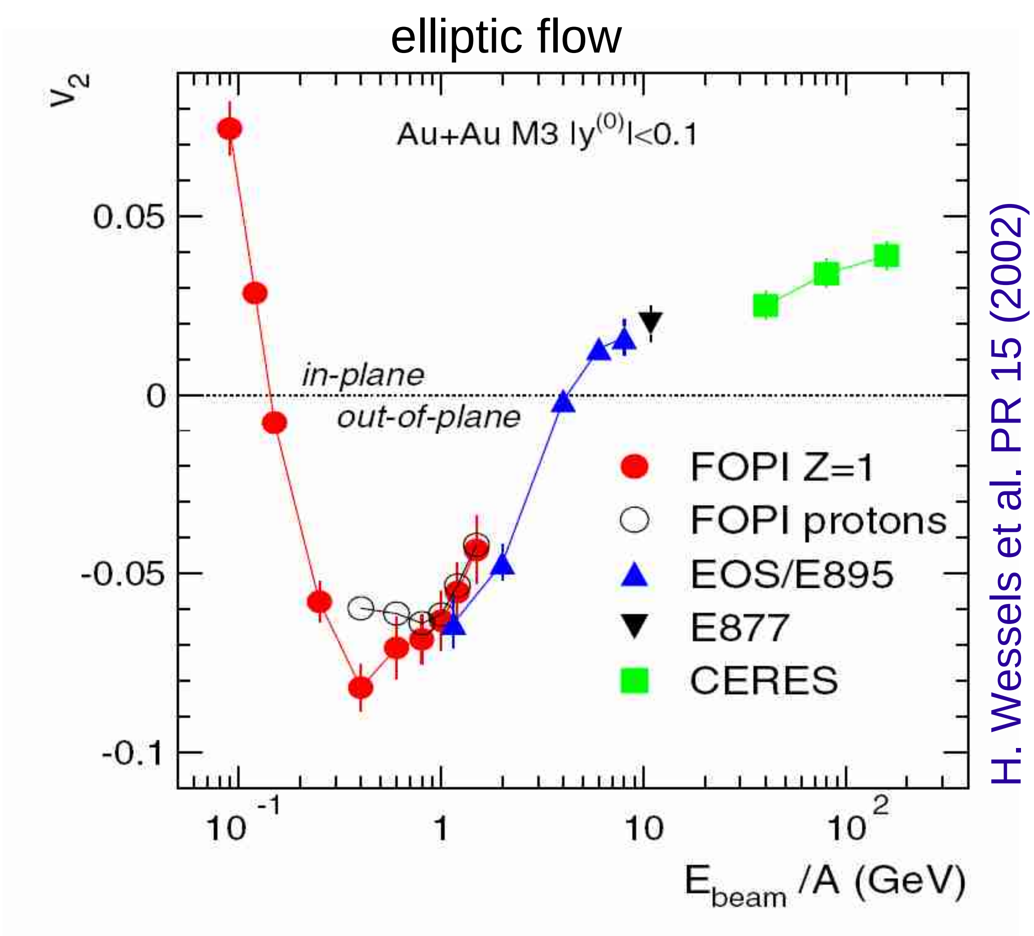
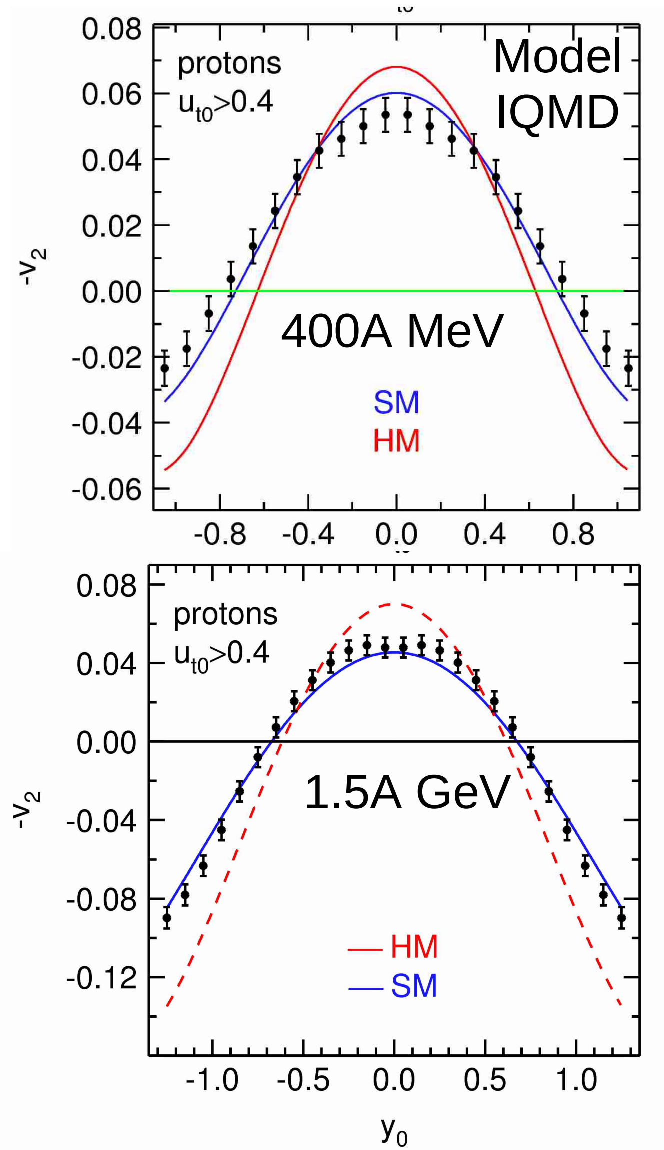


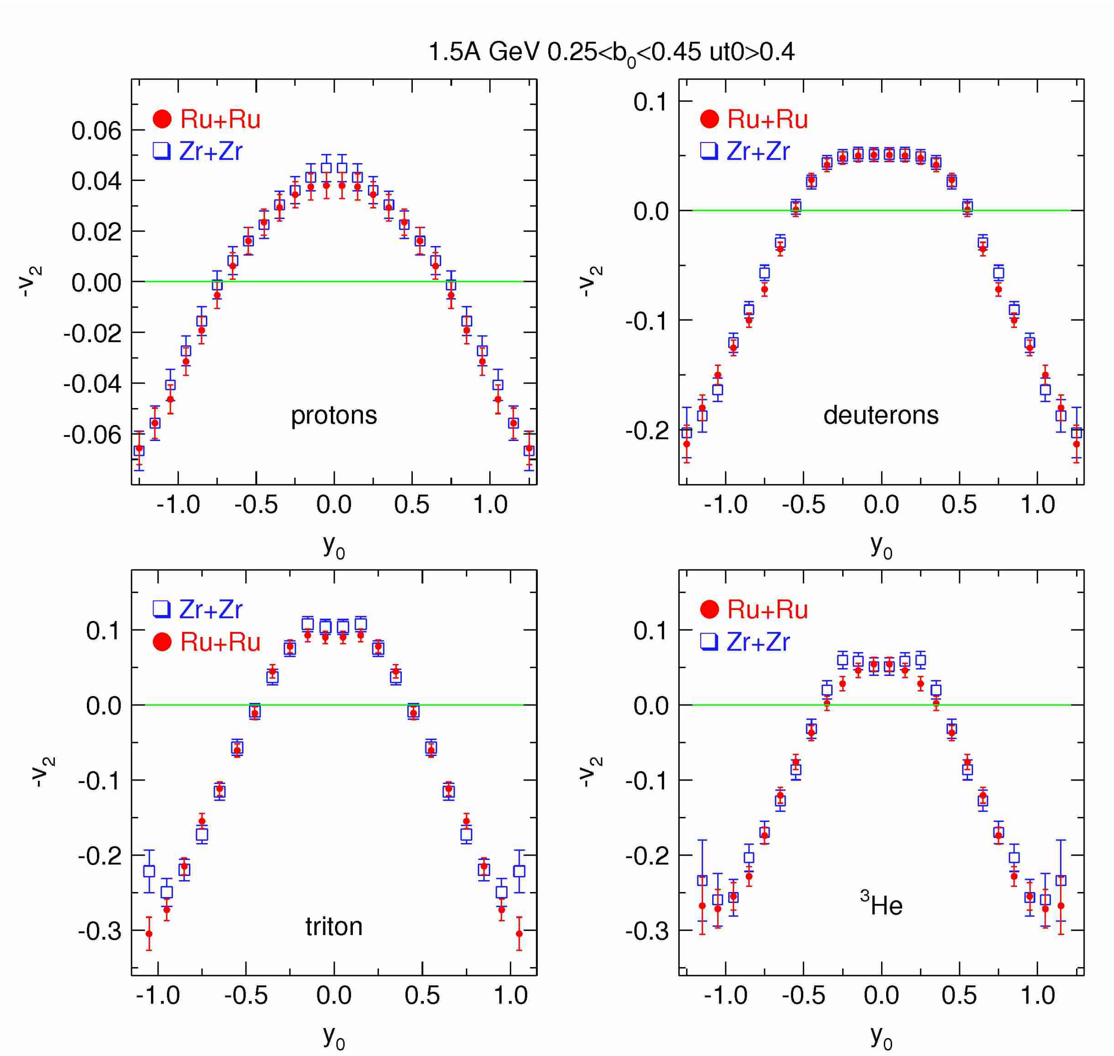
H. Wessels et al. PR 15 (2002)

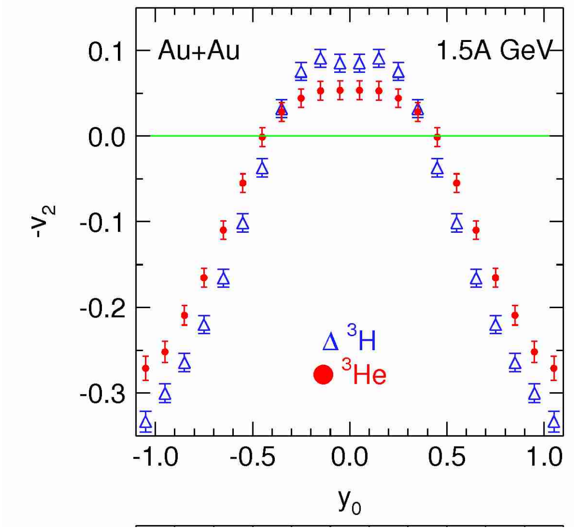
Au+Au



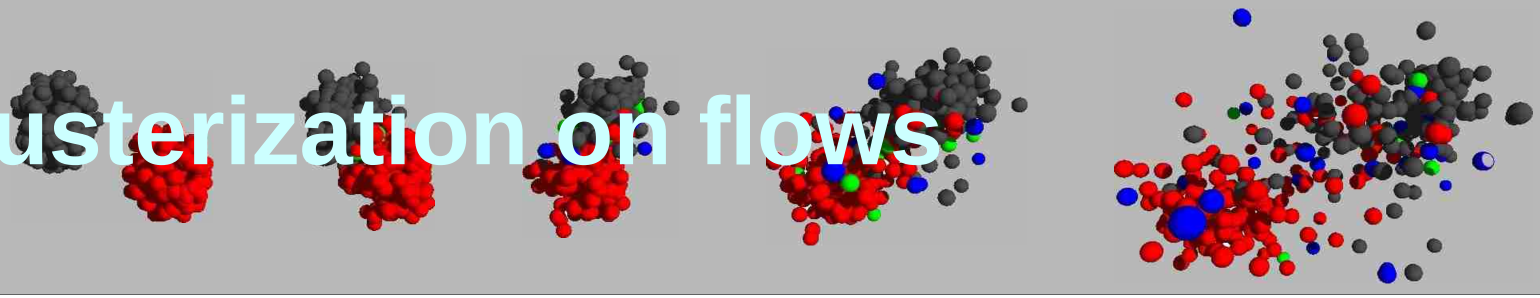
W. Reisdorf et al,
Nucl. Phys. A 876 (2012) 1

Elliptic flow in isospin asymmetric systems





- ^{96}Ru + ^{96}Zr same mass but different charge
- Measurements at 2 energies
- Effects very tiny
- Isospin difference?
- difference for t/3He only at highest energies in Au+Au
- momentum effect?



Influence of clusterization on flows

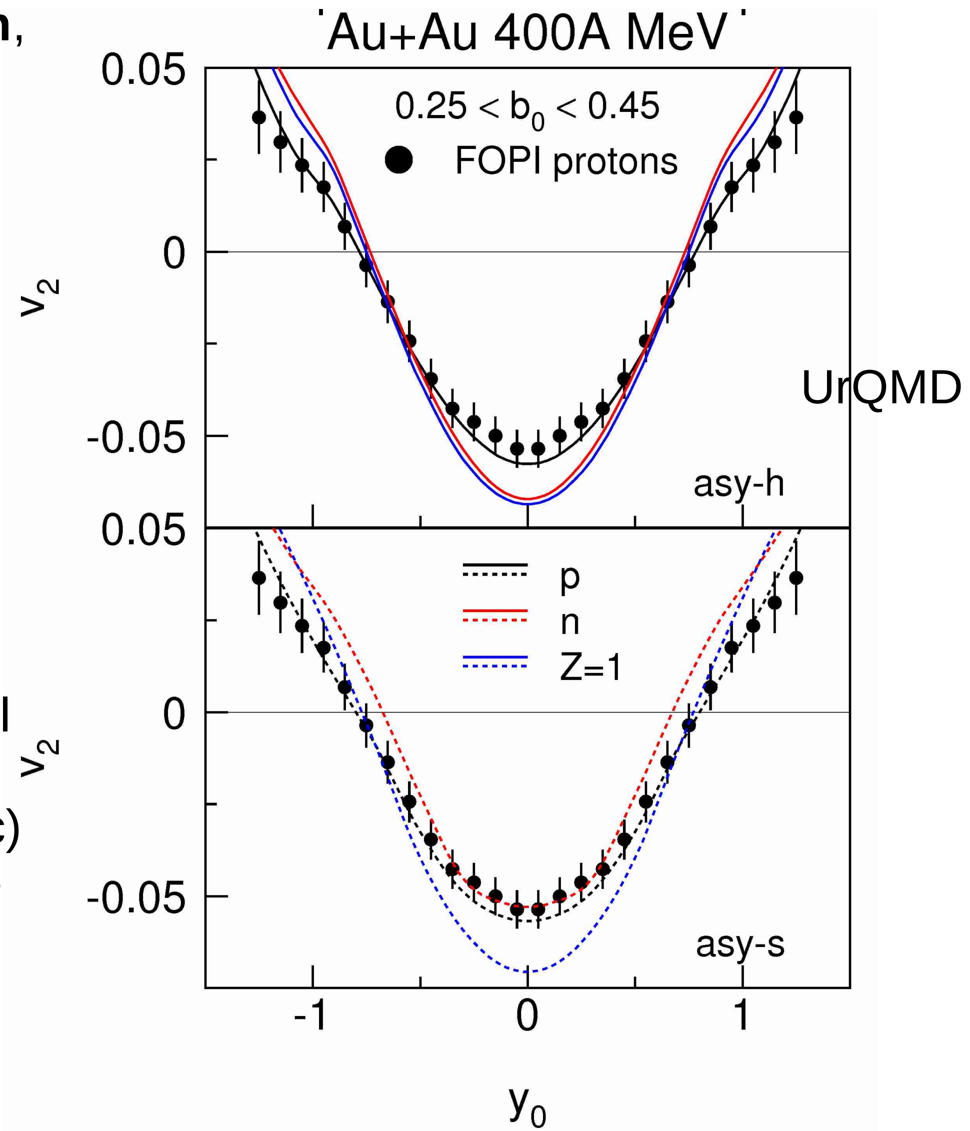
A. LeFevre, C. Hartnack, Y. Leifels, J. Aichelin,

- Z yields can be accounted for with MSTs
- Isotopic effects special treatment
- Influence of cluster formation on flow
- Various studies on the way

Problem with most approaches
start at relatively late times
but
pre-fragments are formed early

Our approach

- Simple algorithm
- Applicable to results of any transport model
- Using potentials of the transport model
- Starting formation of clusters early (40 fm/c)
- Using an Metropolis algorithm to obtain the most stable configuration
- Propagation in Coulomb field
- Eventually deexcitation by evaporation



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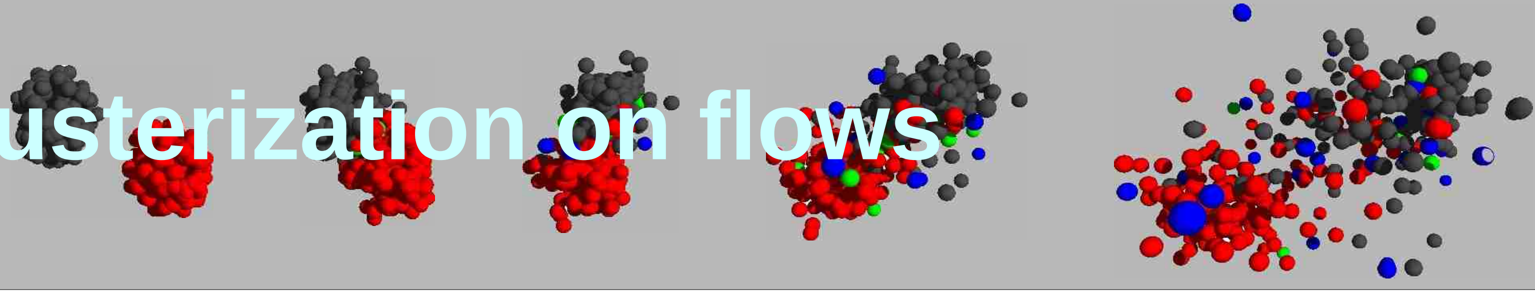

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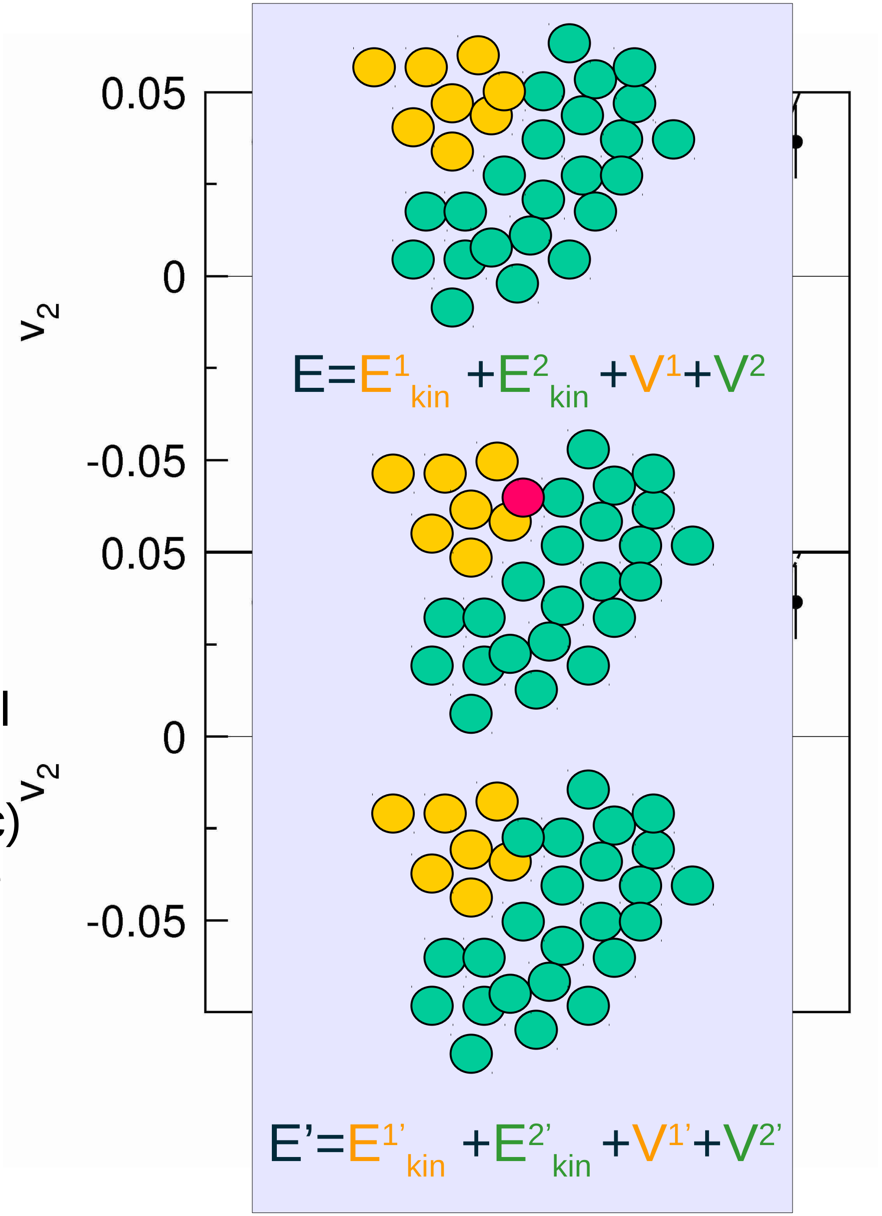
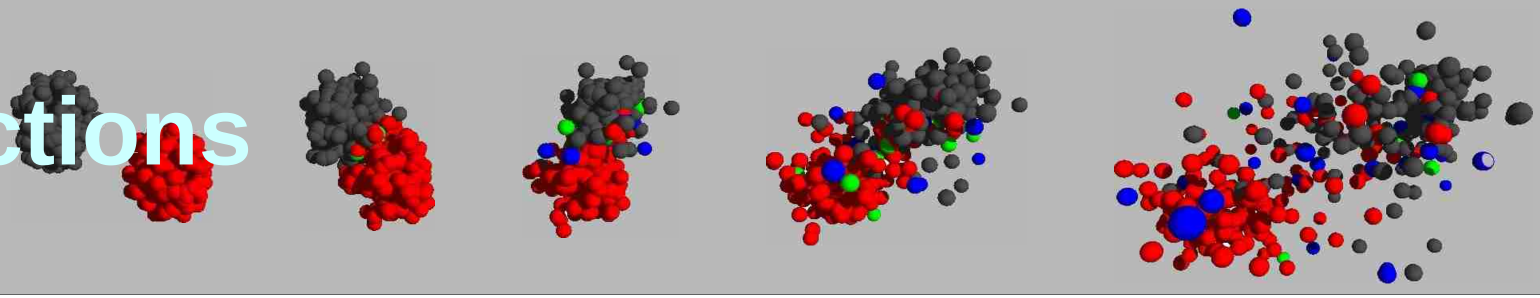
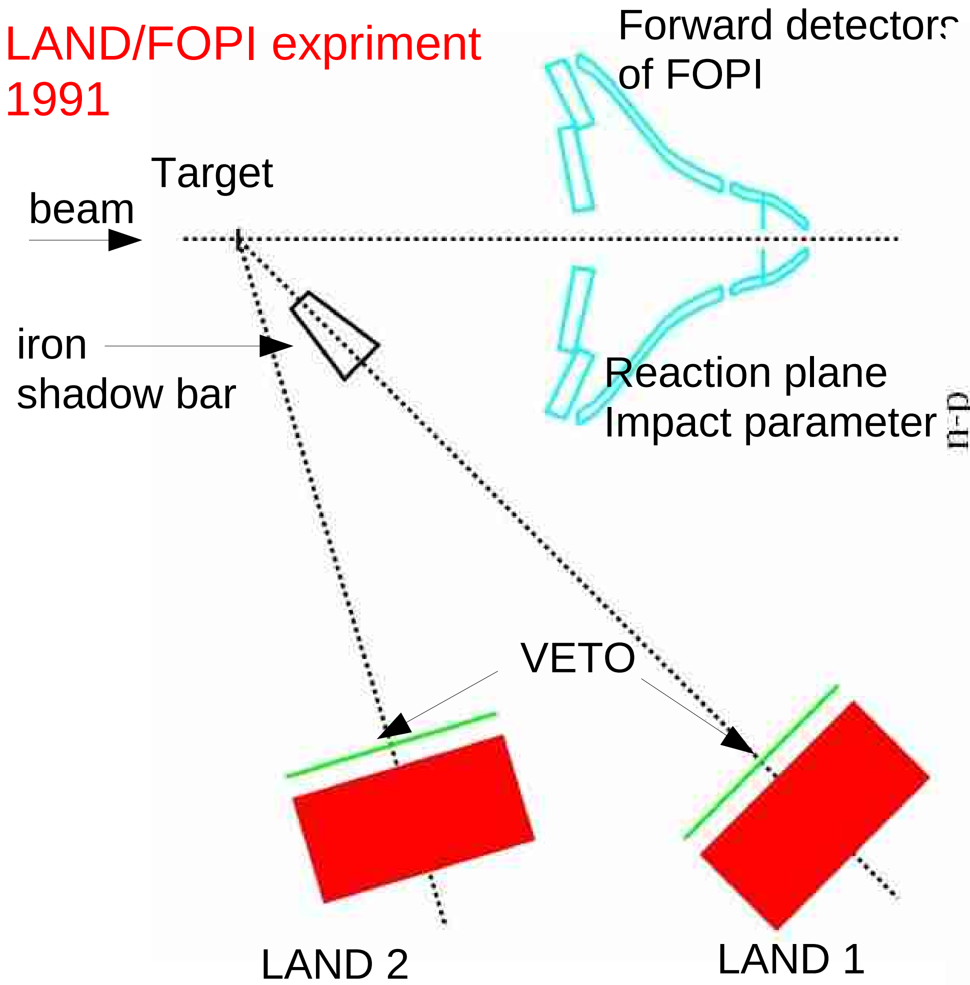
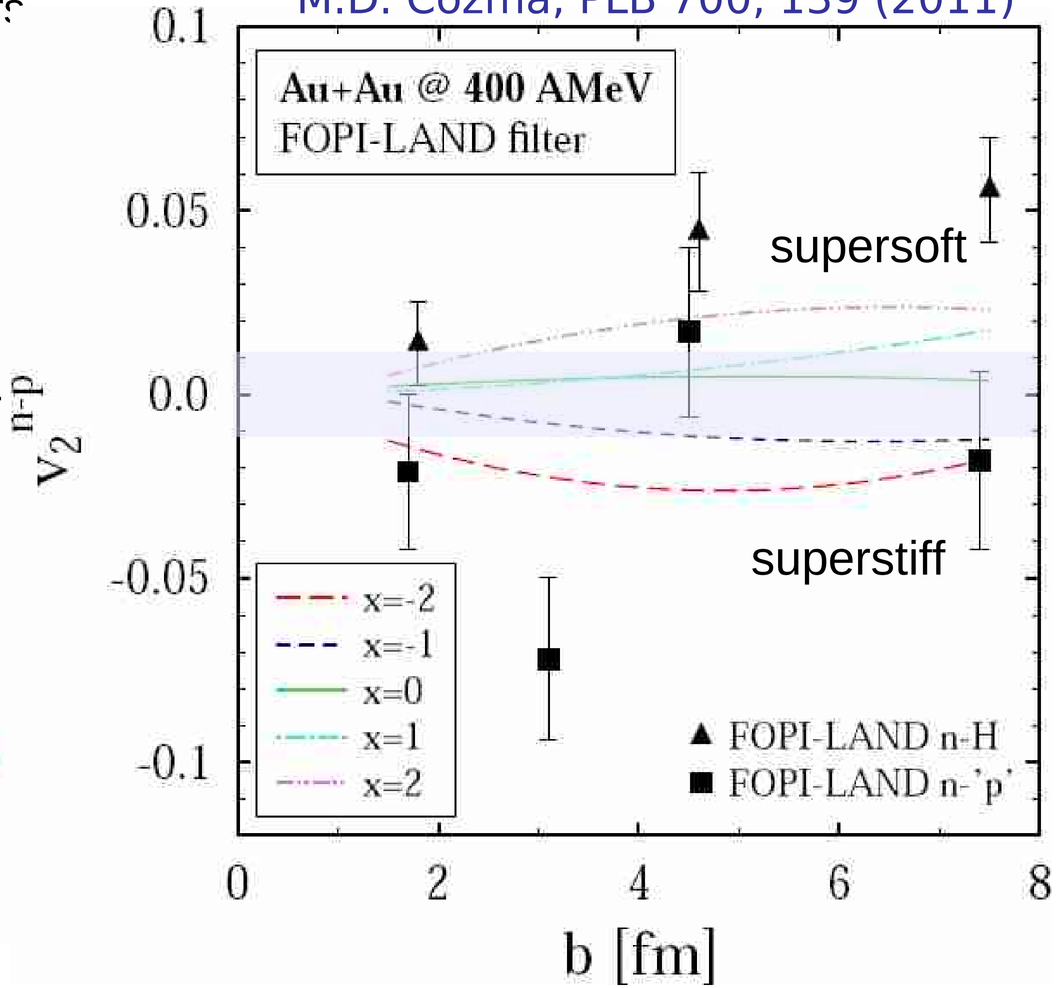




n-p elliptic flow

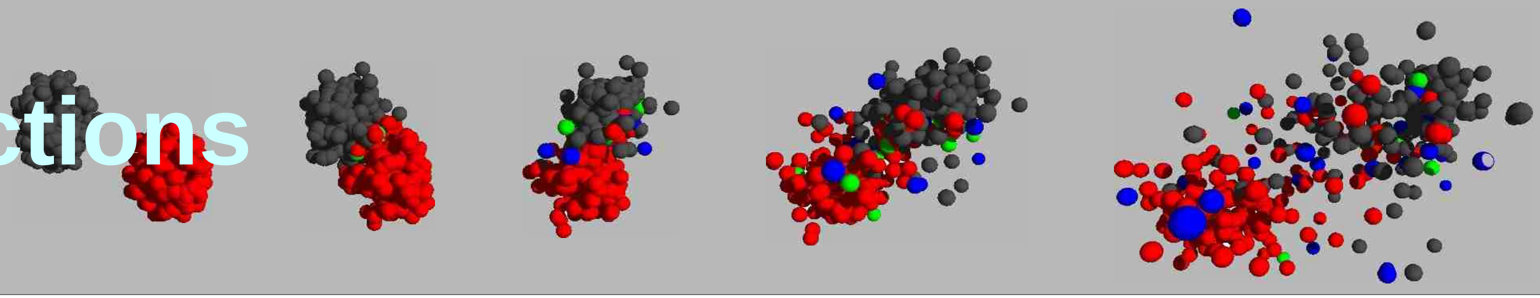


M.D. Cozma, PLB 700, 139 (2011)



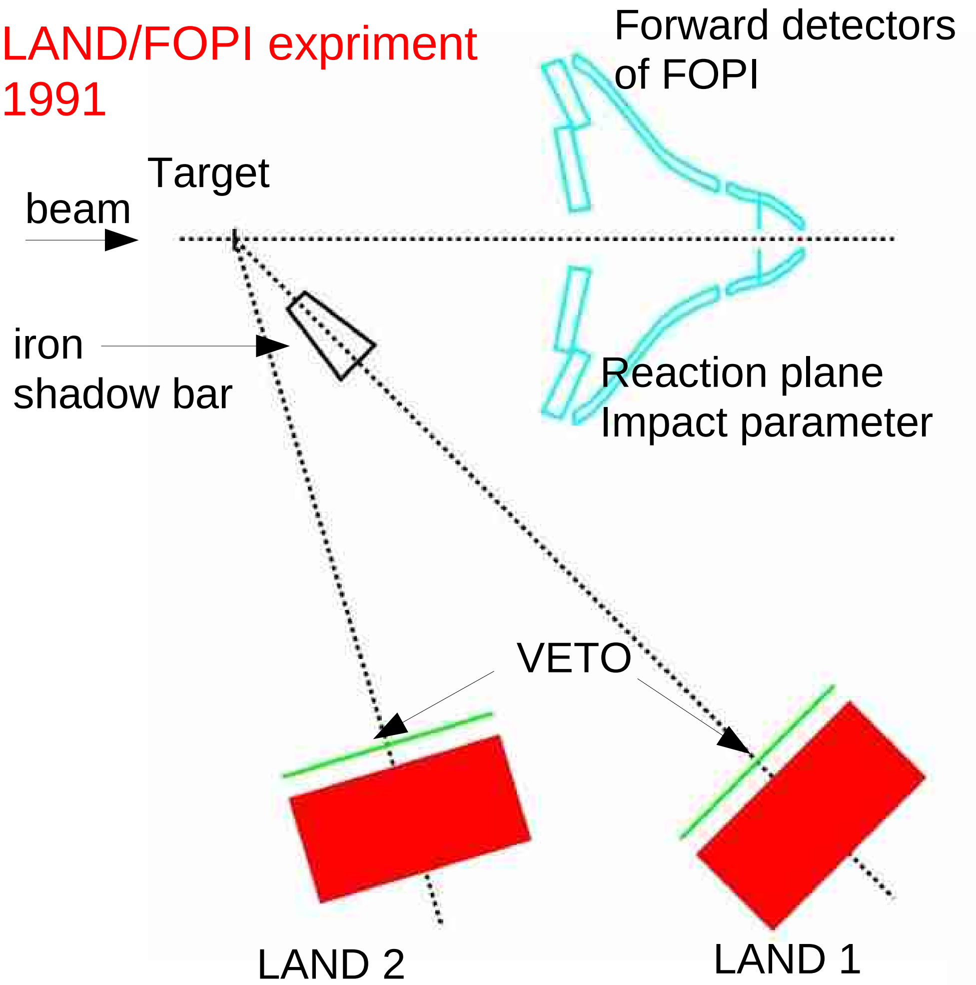
Data: Y. Leifels, D. Lambrecht

Heavy ion reactions

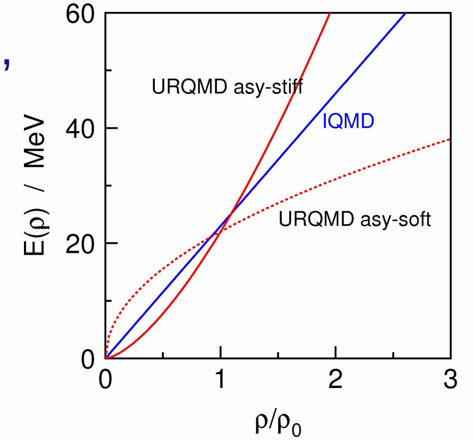


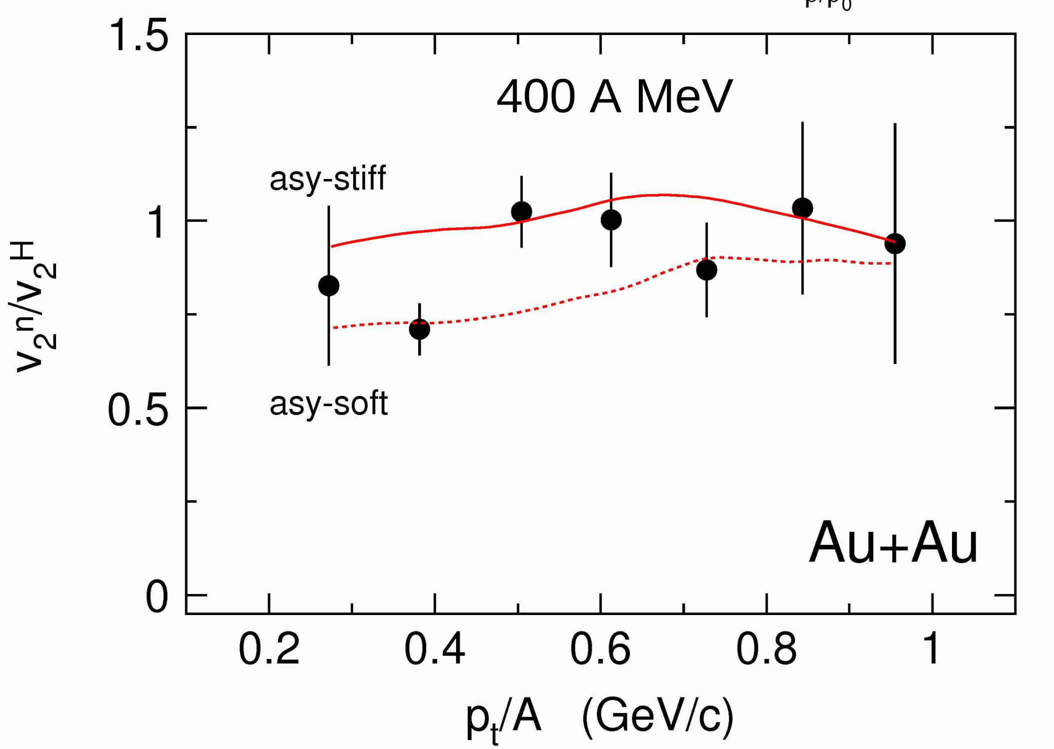
n-p elliptic flow

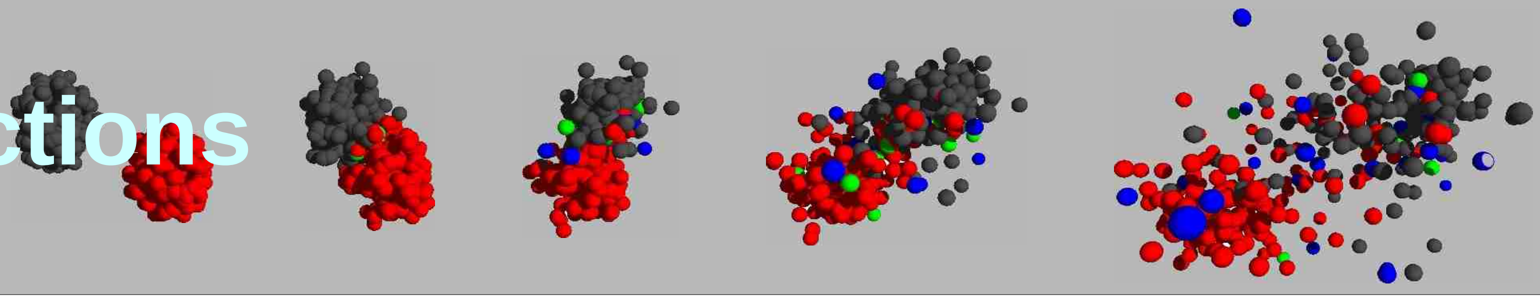
LAND/FOPI expriment
1991



P. Russotto et al.,
PLB 267(2010)

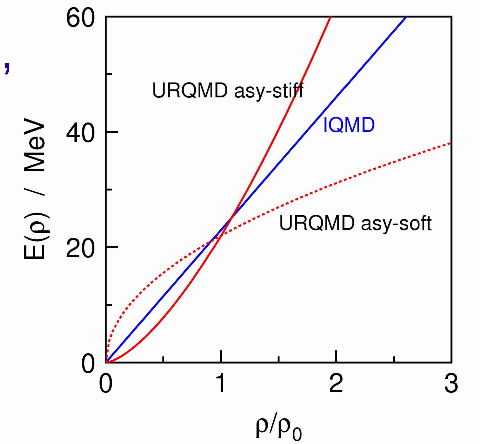






n-p elliptic flow

P. Russotto et al., PLB 267(2010)



Comparison to UrQMD predictions:
Diffent parametrization for in-medium cross sections

neutron/hydrogen

FP1: $\gamma = 1.01 \pm 0.21$

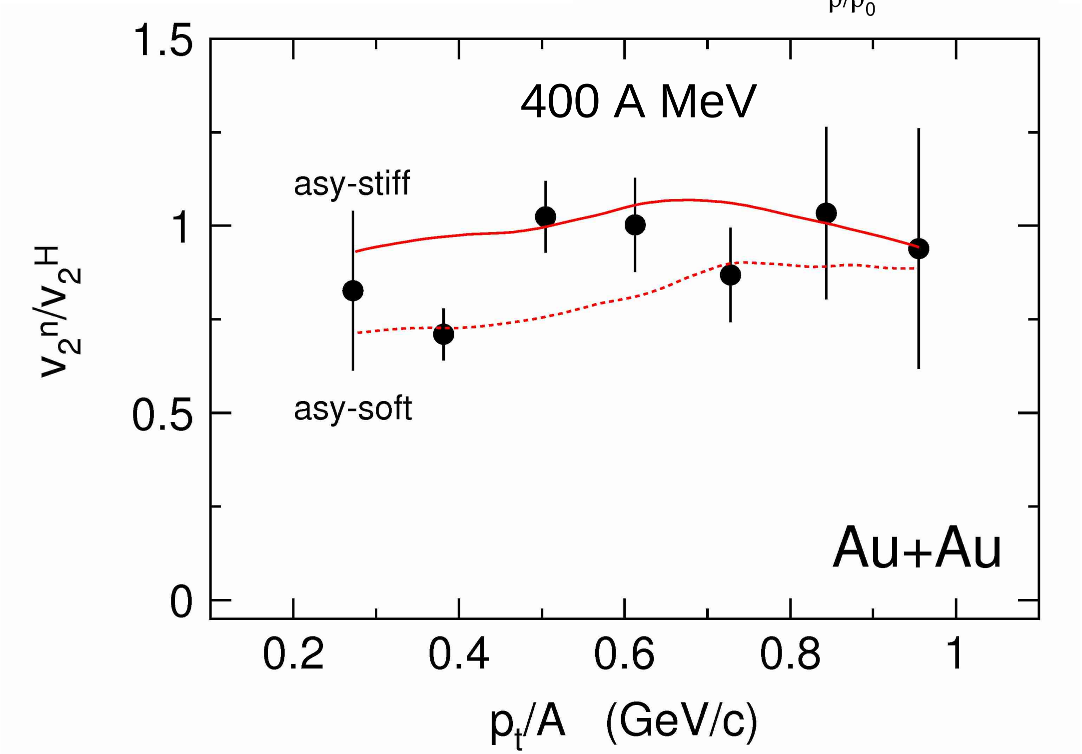
FP2: $\gamma = 0.98 \pm 0.35$

neutron/proton

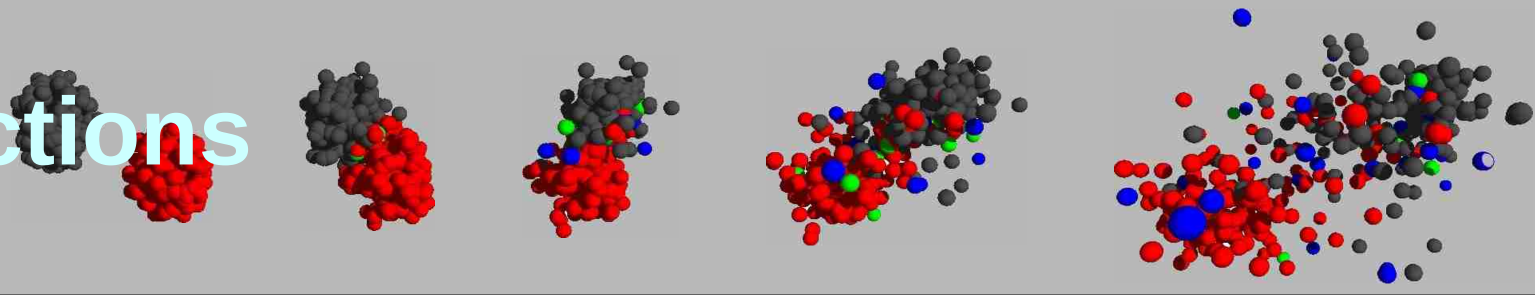
FP1: $\gamma = 0.99 \pm 0.28$

FP2: $\gamma = 0.85 \pm 0.47$

adopted: $\gamma = 0.9 \pm 0.4$

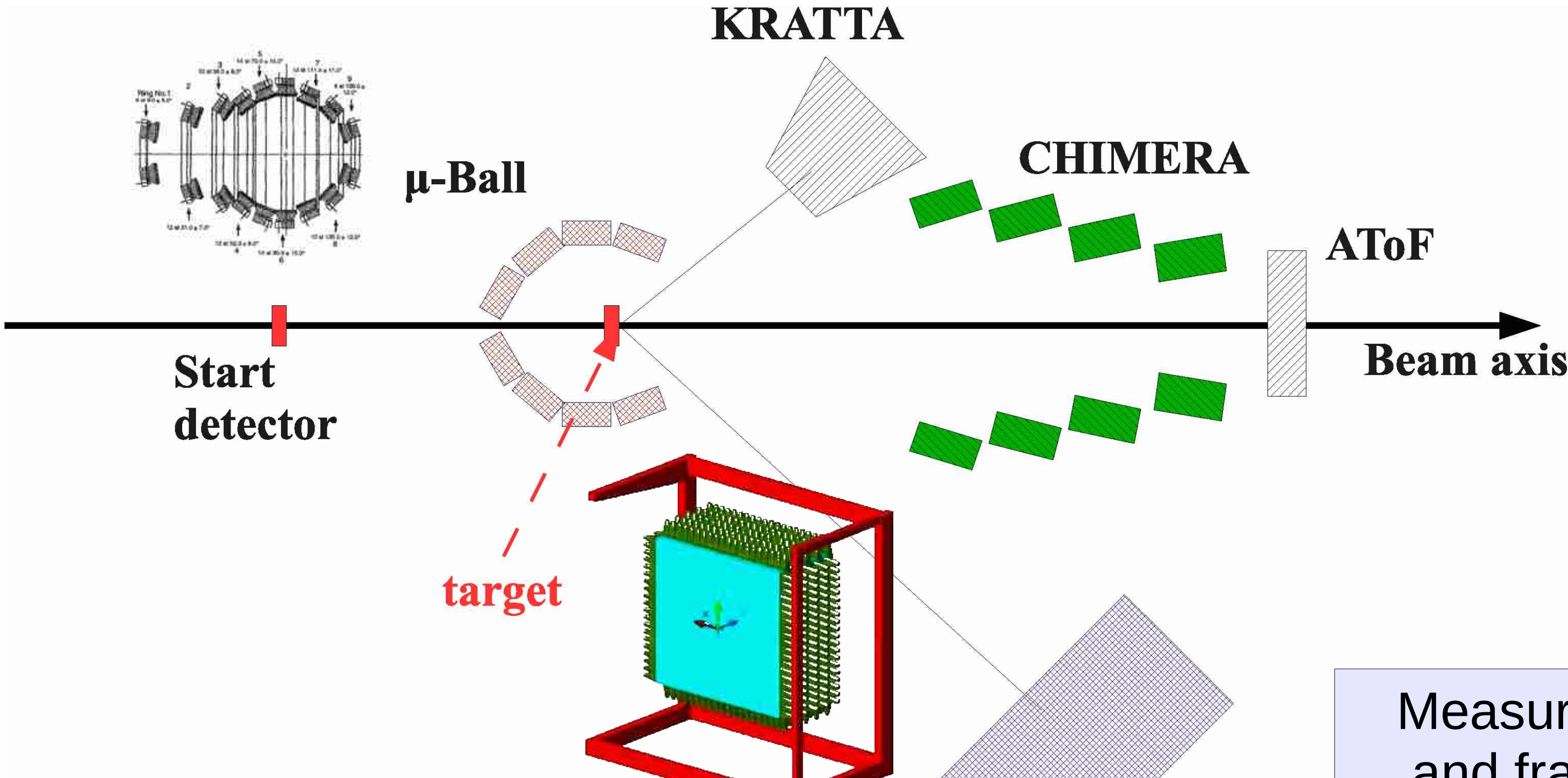


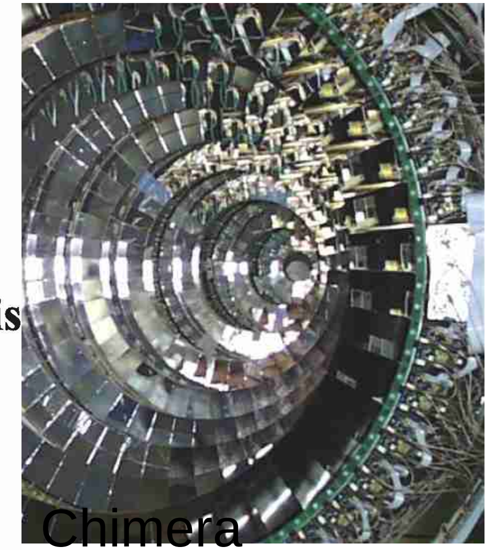
Heavy ion reactions



ASYEOS at SIS 18

Main observable: n/p, t/^{3}He elliptic flow
in Au+Au and ^{96}Ru+Ru(Z=44)/^{96}Zr+Zr(Z=40) collisions at 400 AMeV

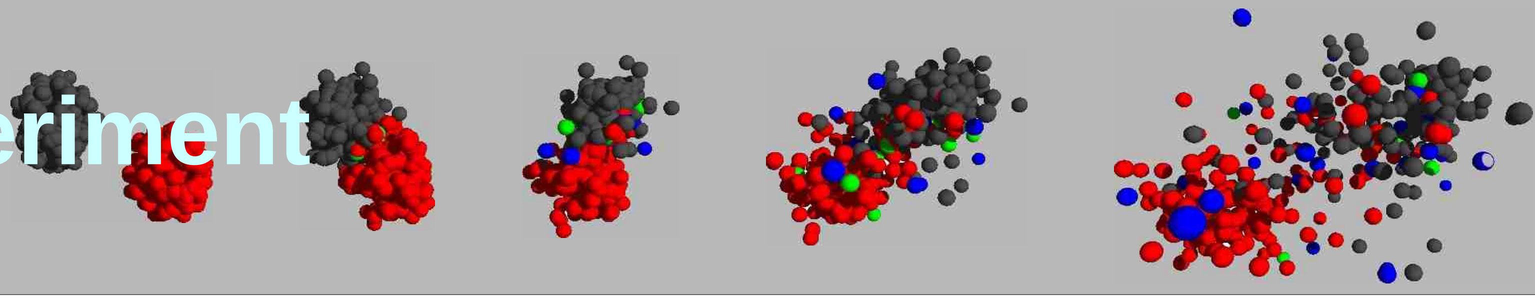


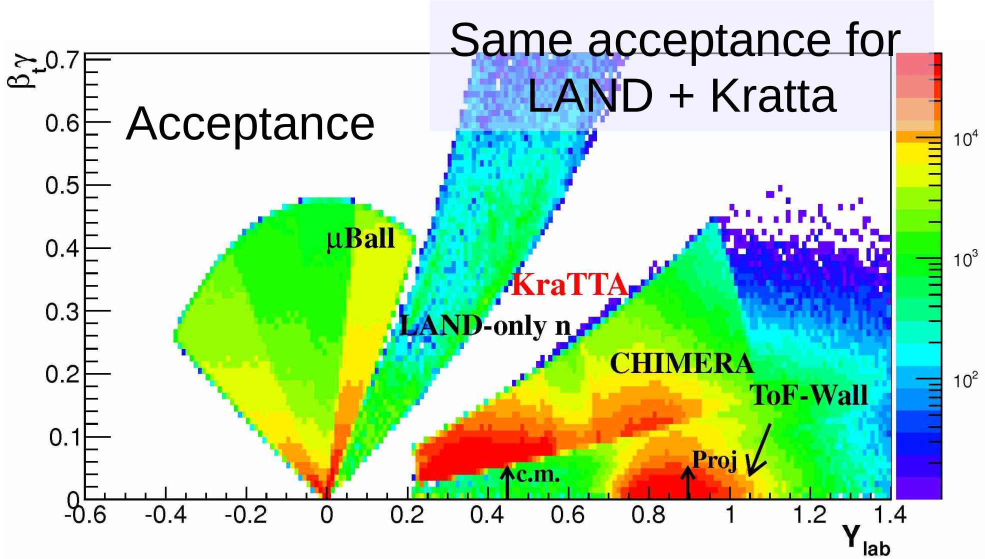


See talk by J. Lukasik
and poster by Simon Gannon

Measure charged particles
and fragments in addition
Clusterisation important

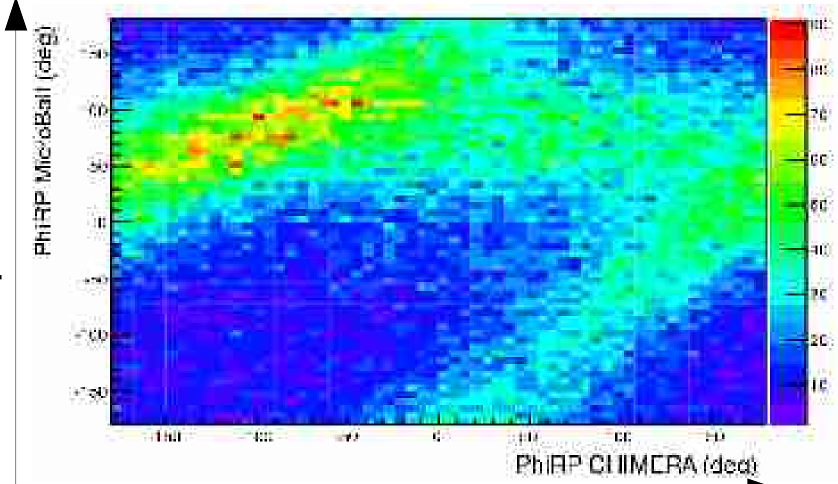
ASY-EOS experiment



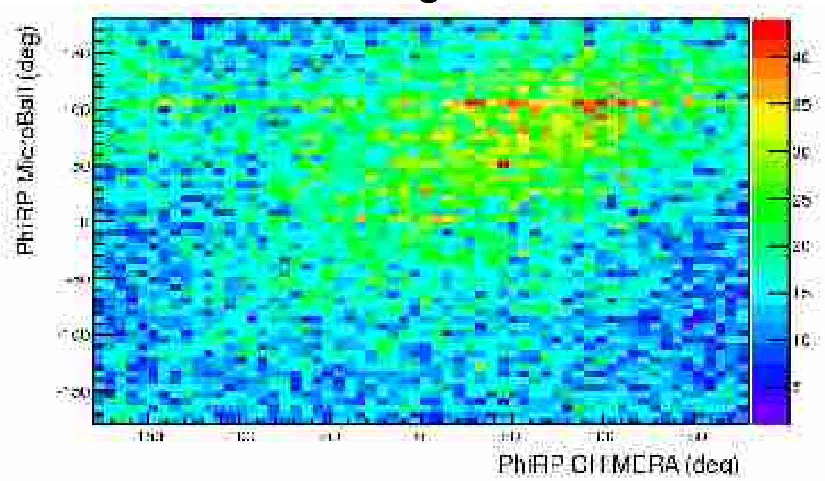


Measuring fragments and neutrons in the same acceptance

Au + Au (2%) 400 AMeV



Au + noTarget 400A MeV

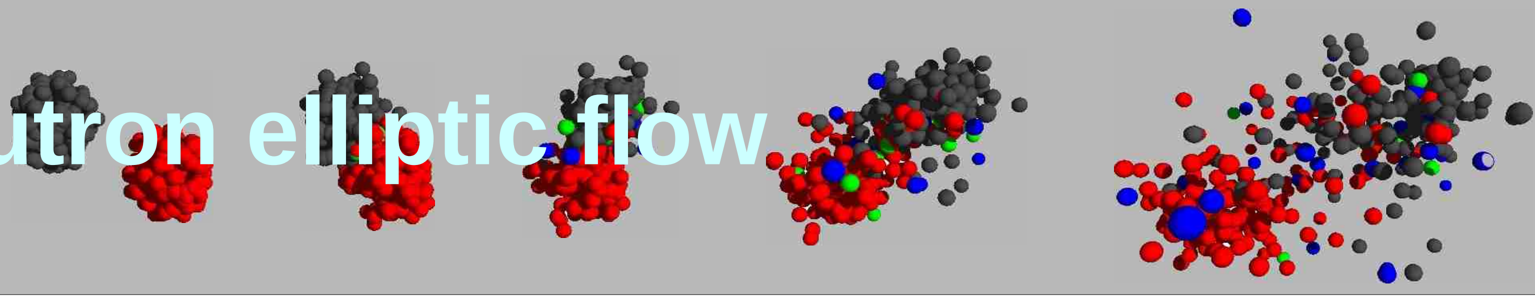


Φ of reaction plane Micro ball

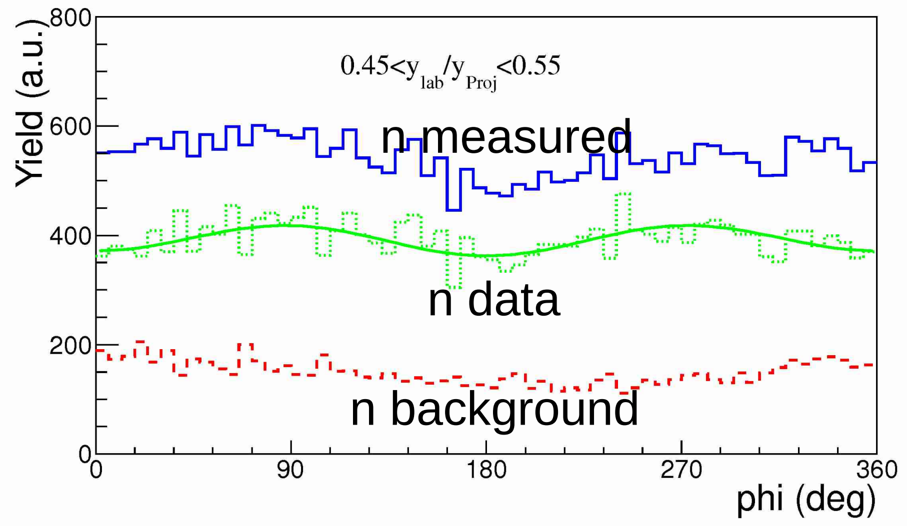
Φ of reaction plane Chimera

P. Russotto et al. (2013)

Results on neutron elliptic flow



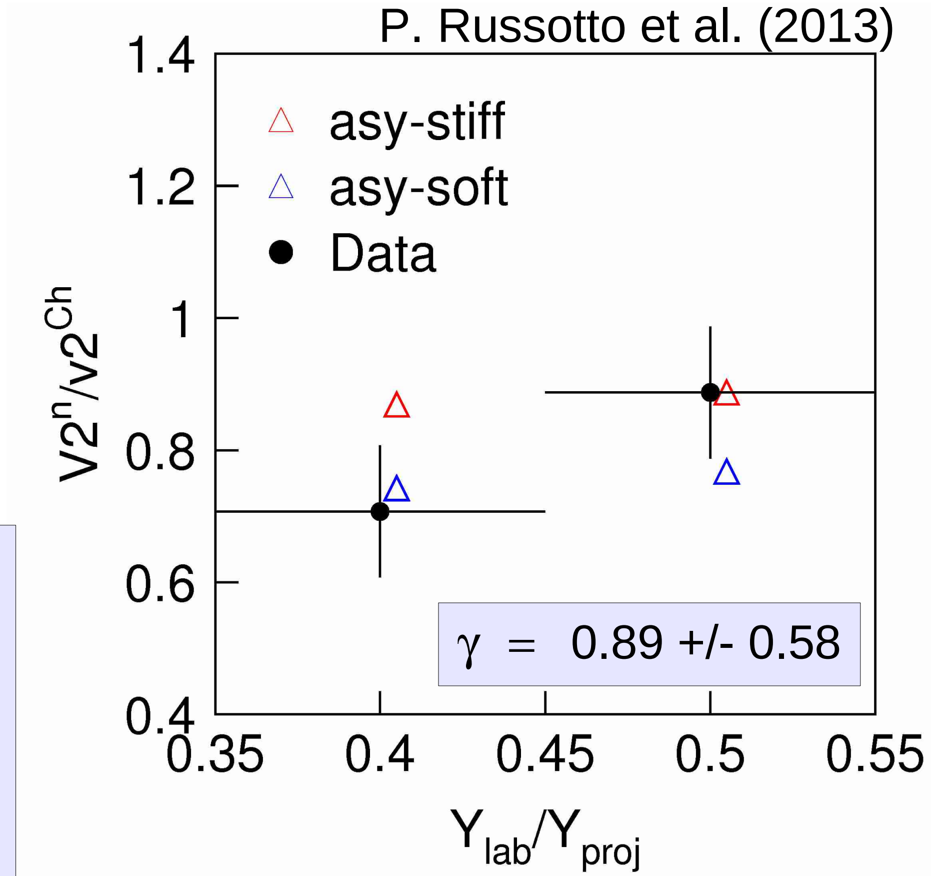
Reaction plane reconstructed



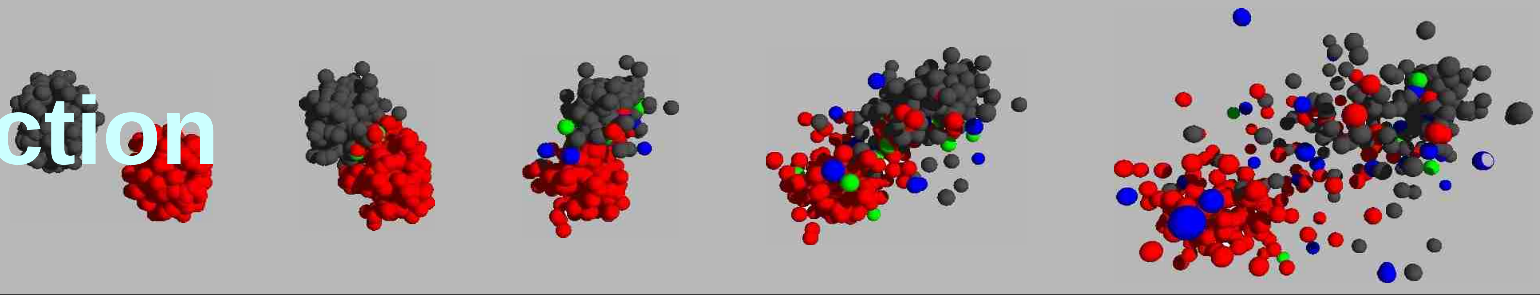
- n background from shadow bar measurements
- preliminary results
  - Comparison of elliptic flow of neutrons and charged particles consistent with previous findings
- Analysis ongoing
- Kratta needed for comparison between neutrons and isotopic resolved charged particles

Preliminary results in comparison to UrQMD calculations

P. Russotto et al. (2013)



Particle production



Symmetry energy via production of isospin partners $\pi^{+/-}$ and $K^{0/+}$

π-/π+ ratio sensitive to (N/Z) of system

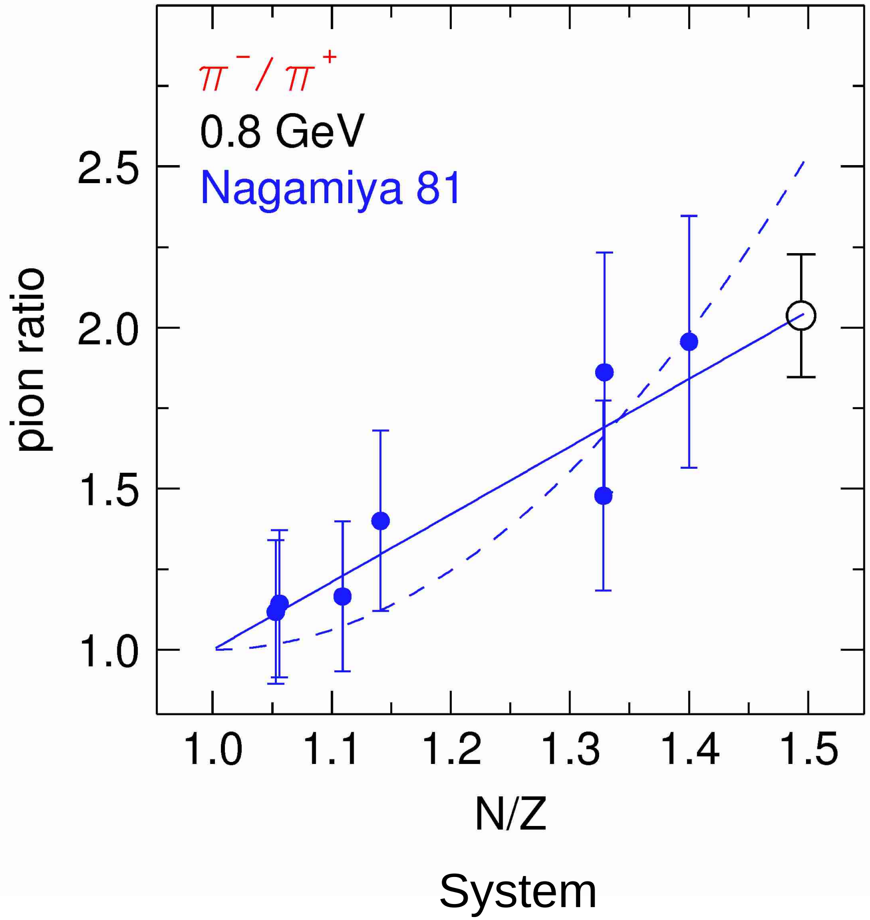
$$\frac{\pi^-}{\pi^+} = \frac{5N^2+NZ}{5Z^2+NZ} \approx \left(\frac{N}{Z}\right)^2$$

$NN \Leftrightarrow N\Delta \Leftrightarrow \pi NN$ isobar model

π-/π+ ratio sensitive to
n and p effetive masses

$$\frac{\pi^-}{\pi^+} \equiv \exp \frac{2(\mu_n - \mu_p)}{T}$$

chemical equilibrium



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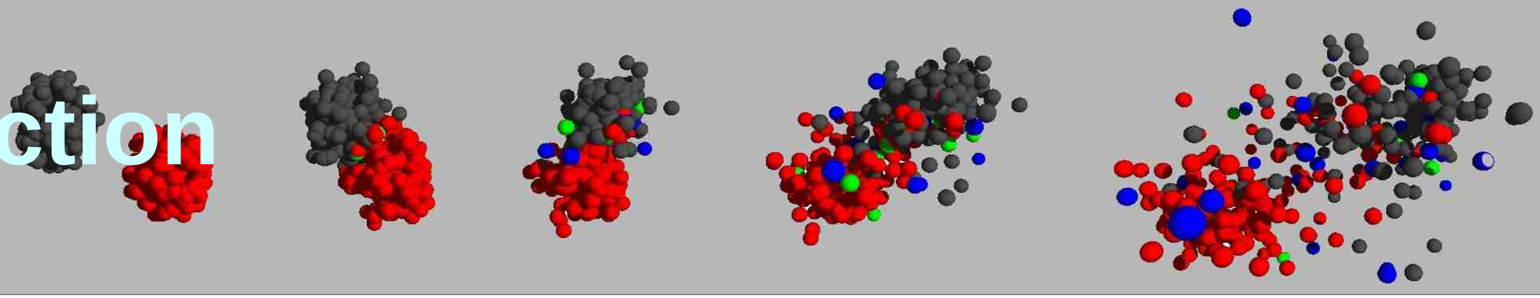

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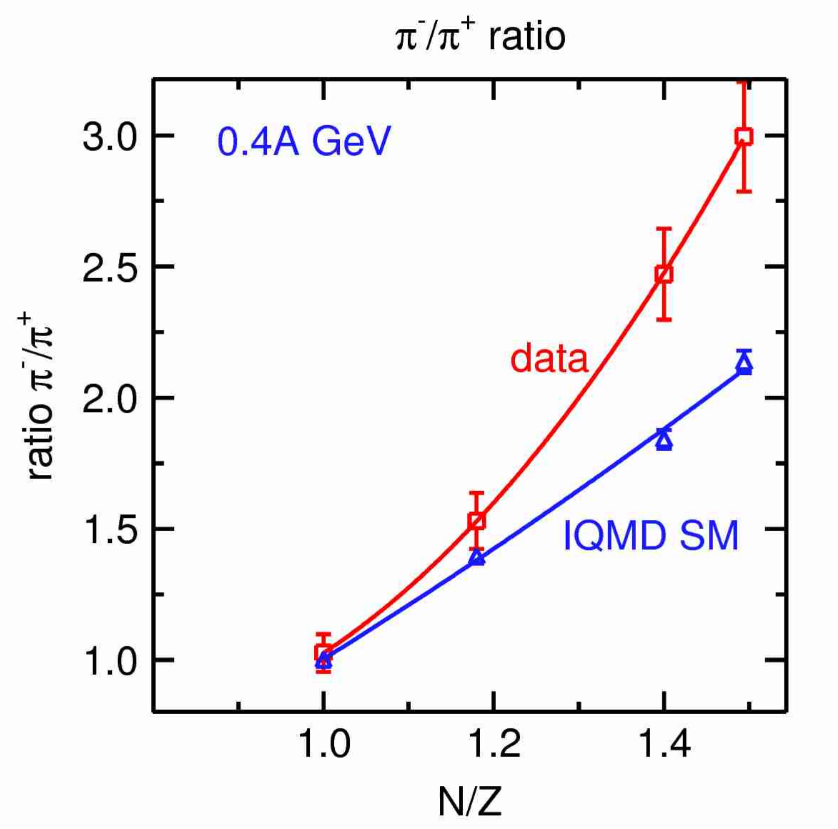
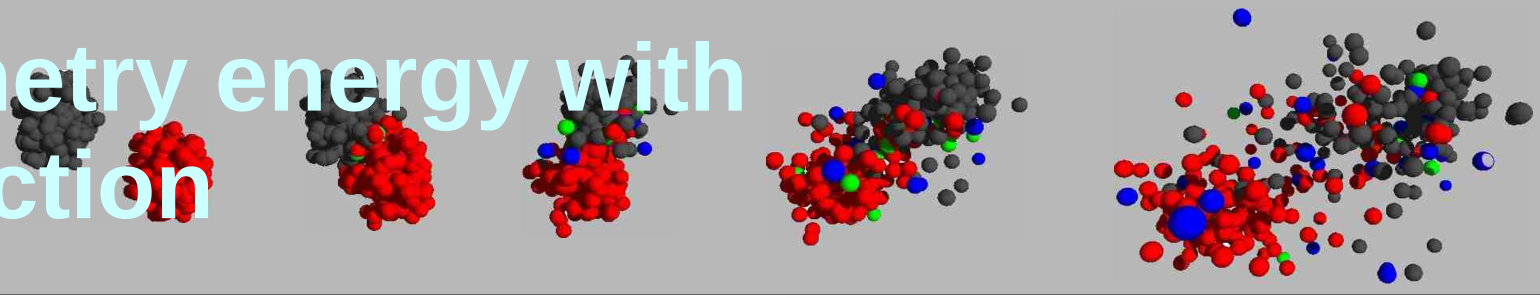
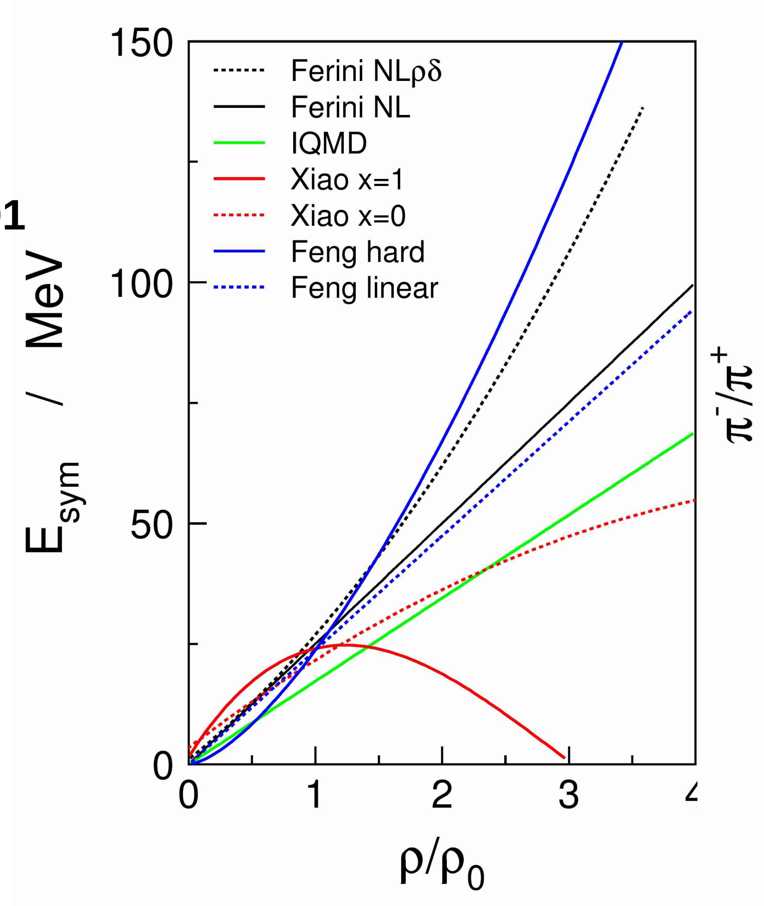


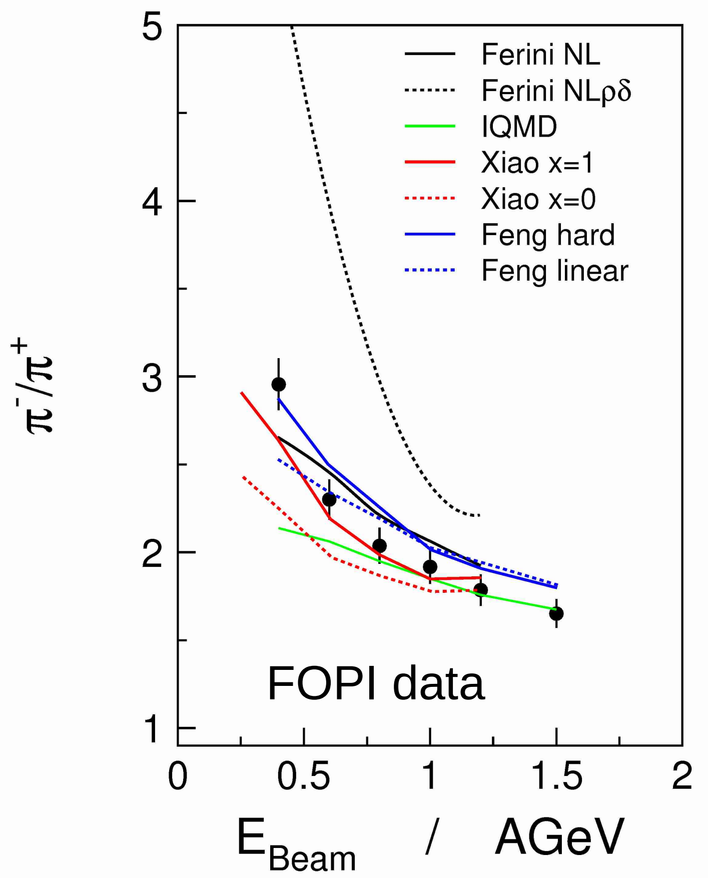
System

Probing symmetry energy with particle production



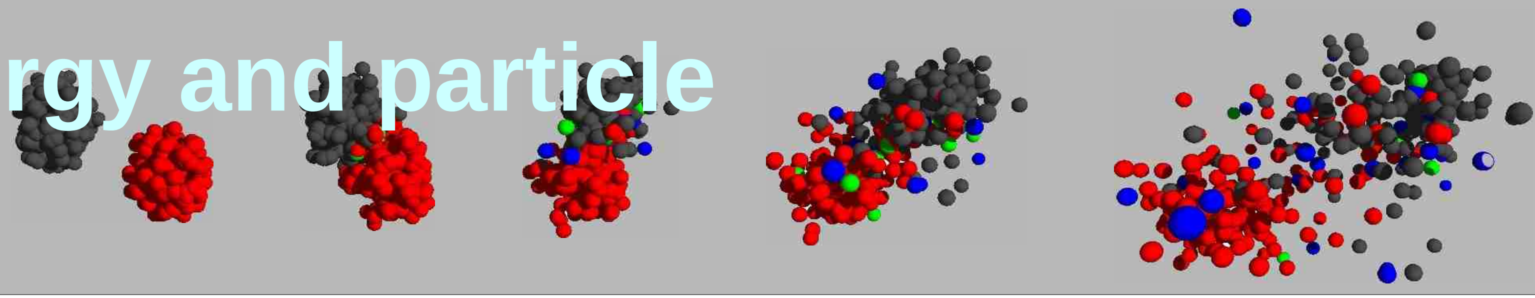
Z. Xiao et al. PRL 102 (2009) 62502
J. Xie et al, PLB 718 (2013)
J. Xu et al., nucl-the 1305.0099
G. Ferini et al. PRL 97 (2006) 202301
Feng et al, nucl-th 0907.2990
C. Hartnack, J. Aichelin (2013)



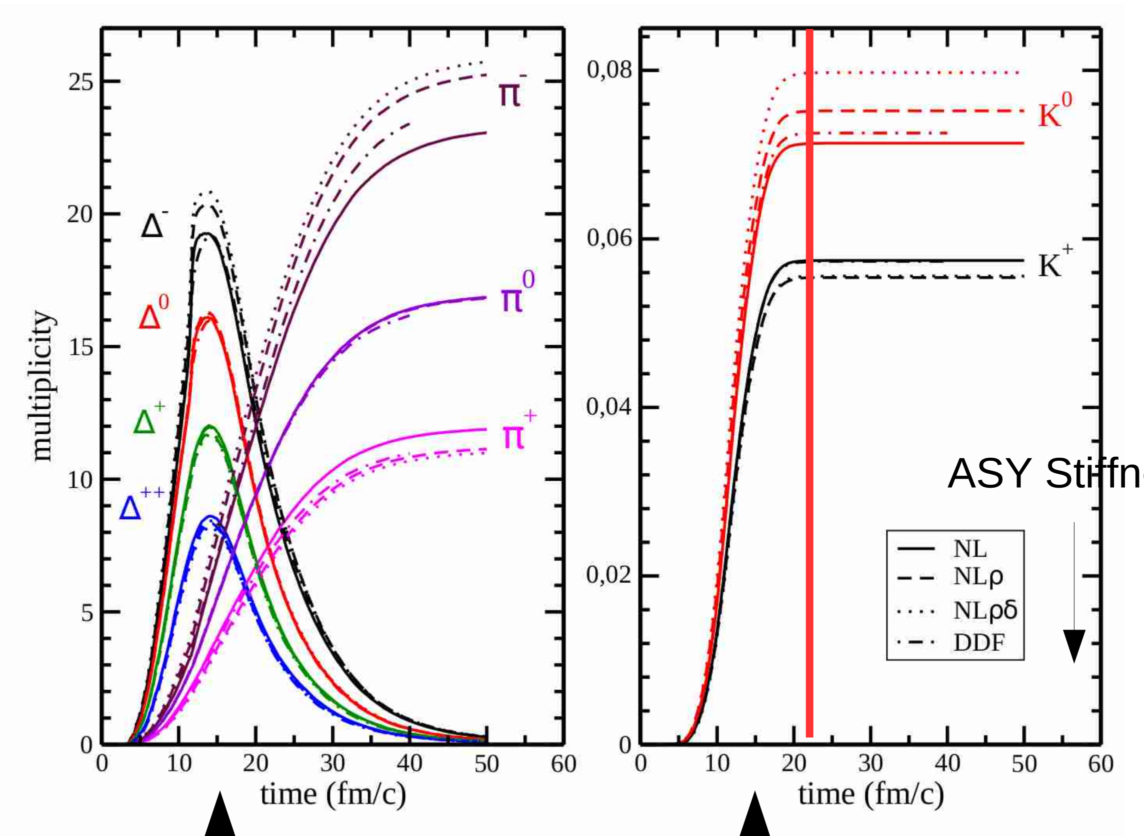


Results model dependent
BECAUSE
Symmetry energy → n/p ratio, number of nn, np, pp collisions
Medium → effective masses (N, π, Δ), cross sections
→ thresholds
→ interpretation of pion data not straight forward

Symmetry energy and particle production



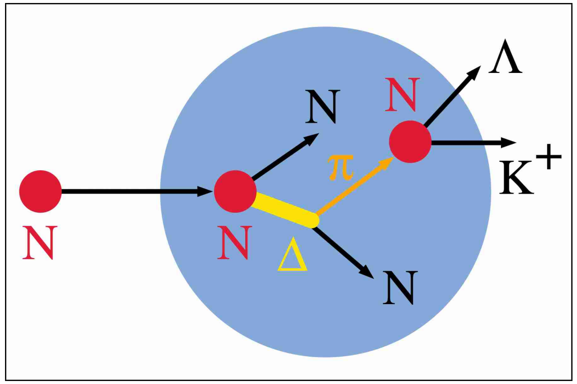
G.Ferini et al.,PRL 97 (2006) 202301



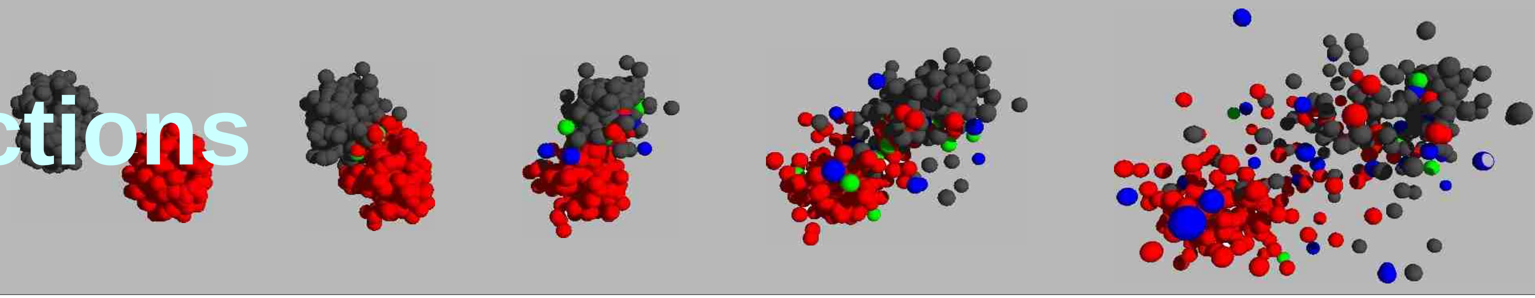
max. density

Kaons

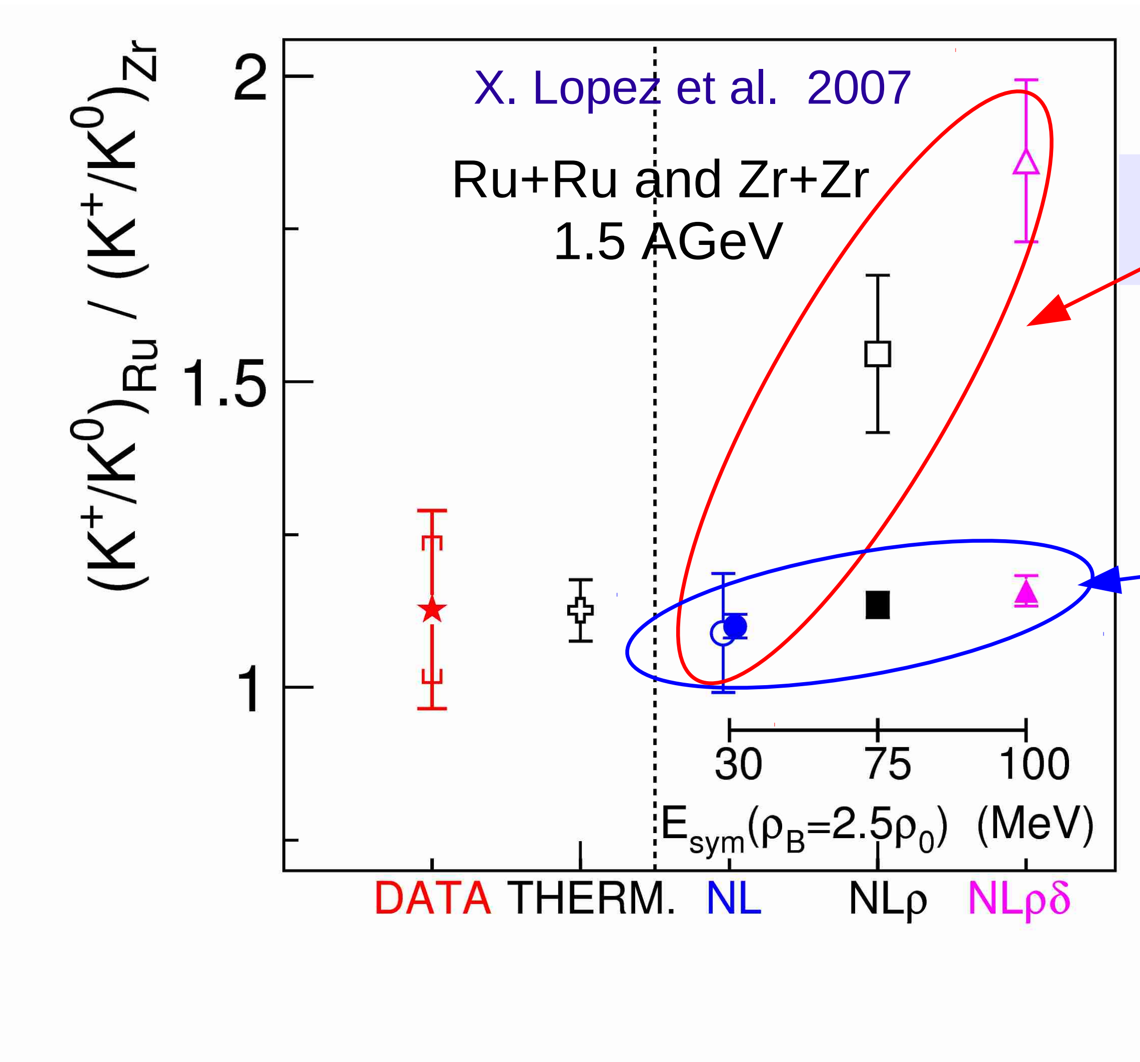
- High threshold
- Subthreshold production is sensitive to density → sym EOS
- Weakly interacting with medium, long mean free path
- Early freeze-out
- Kaon number stable after 20 fm/c



Heavy ion reactions



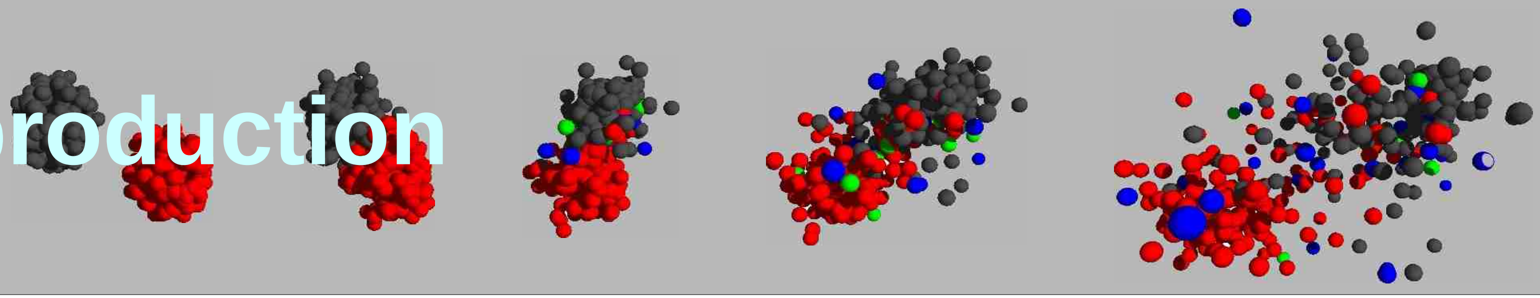
Very high densities - Kaon production

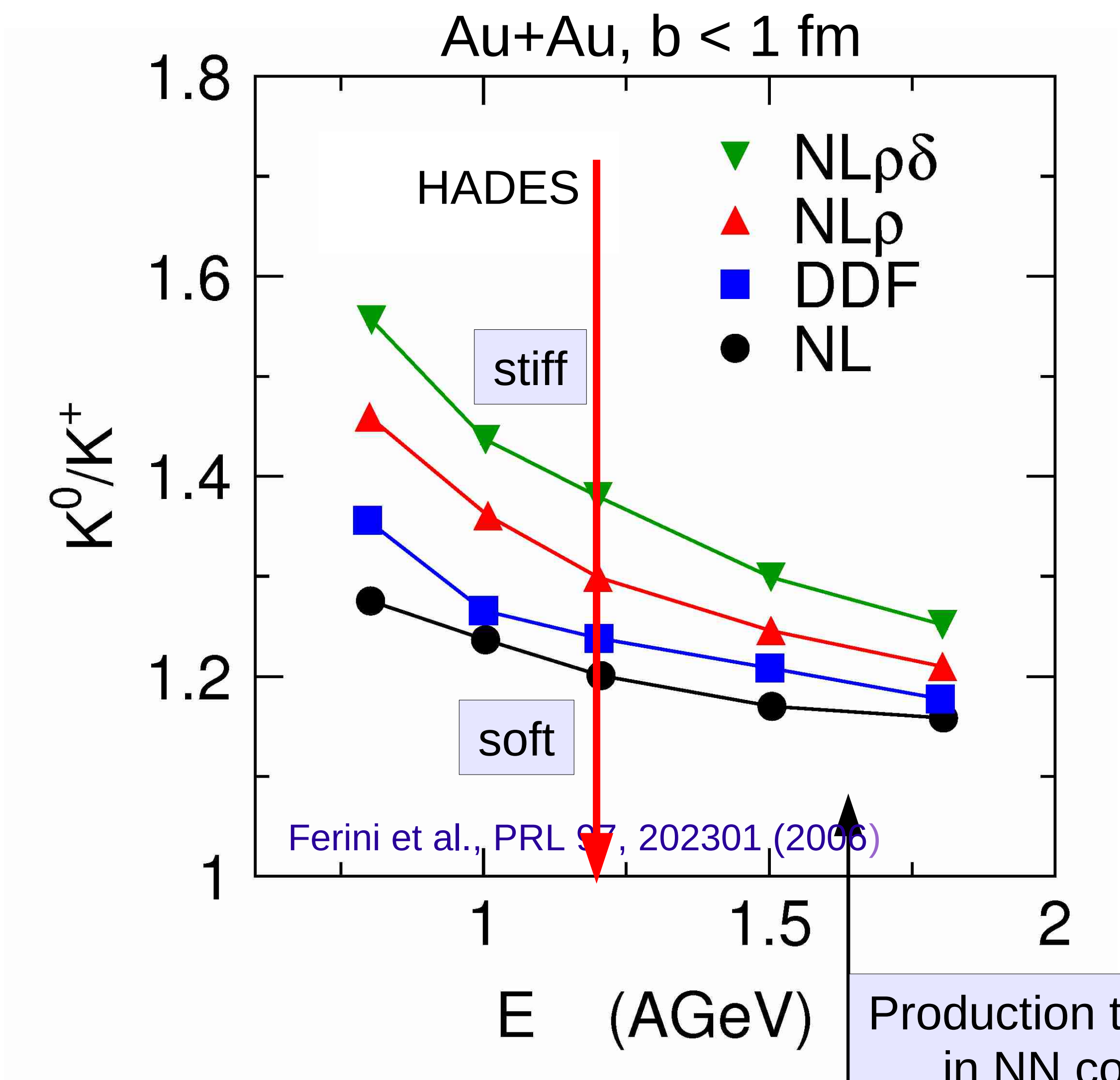


Infinite nuclear matter calculation

Nucleus nucleus collision

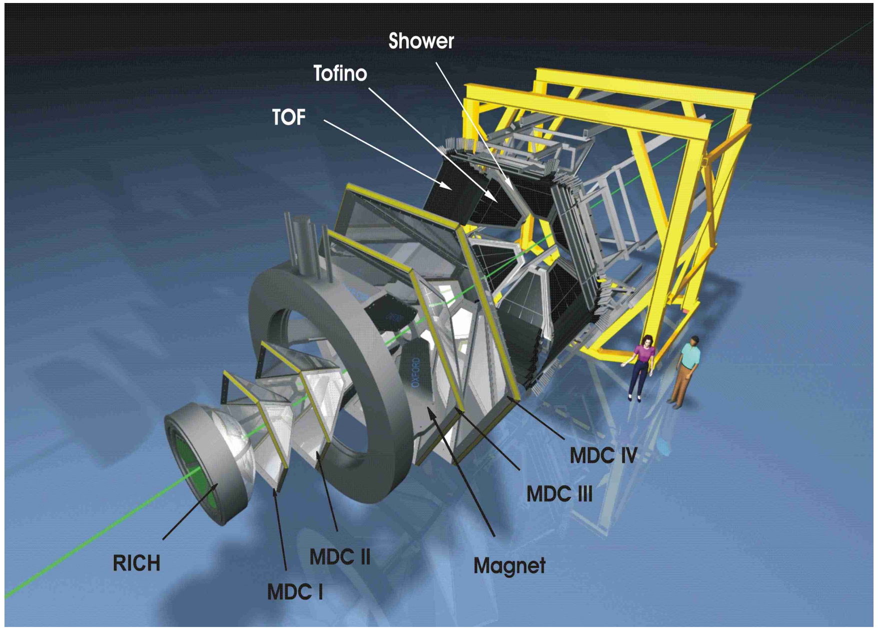
Strangeness production





Production threshold in NN collision

- higher sensitivity at lower energies
- requires excellent kaon identification and long beam times
- HADES



Poster by H. Schuldes

Summary

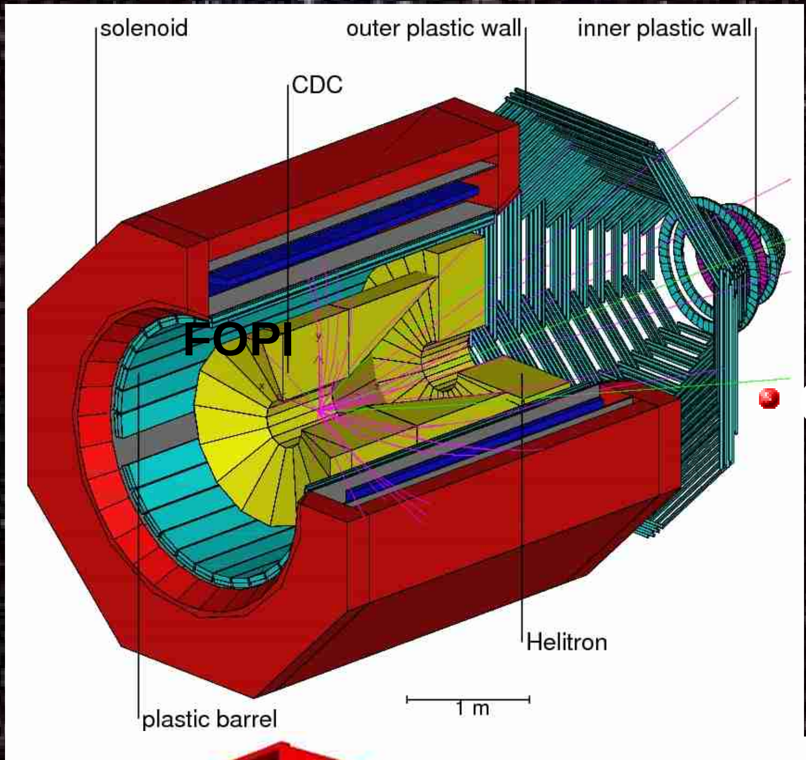
Constraining symmetry energy at high densities

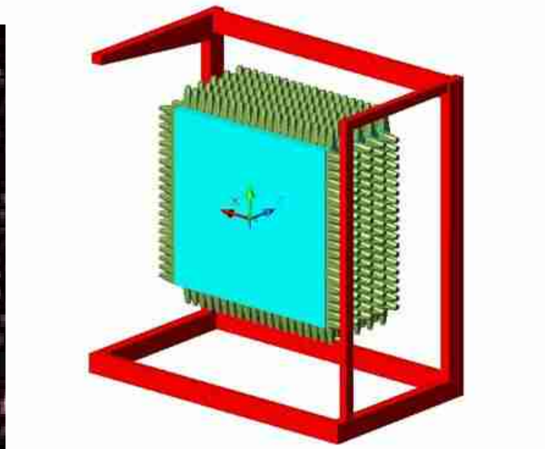
by measuring

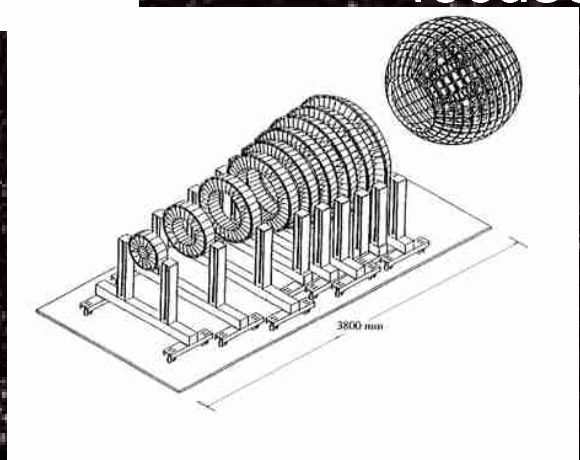
- $t/^3He$, n/p, π^-/π^+, K^0/K^+ particle yields, differential flows, double ratios etc. with stable beams
- relevant energies 400-2000 AMeV
- Old and preliminary new results point to a moderately hard SE $\gamma = 0.9$
- Exception pions → soft SE?
- Several efforts ongoing
- focused on two observables

flow of n/p, $t/^3He$

strangeness



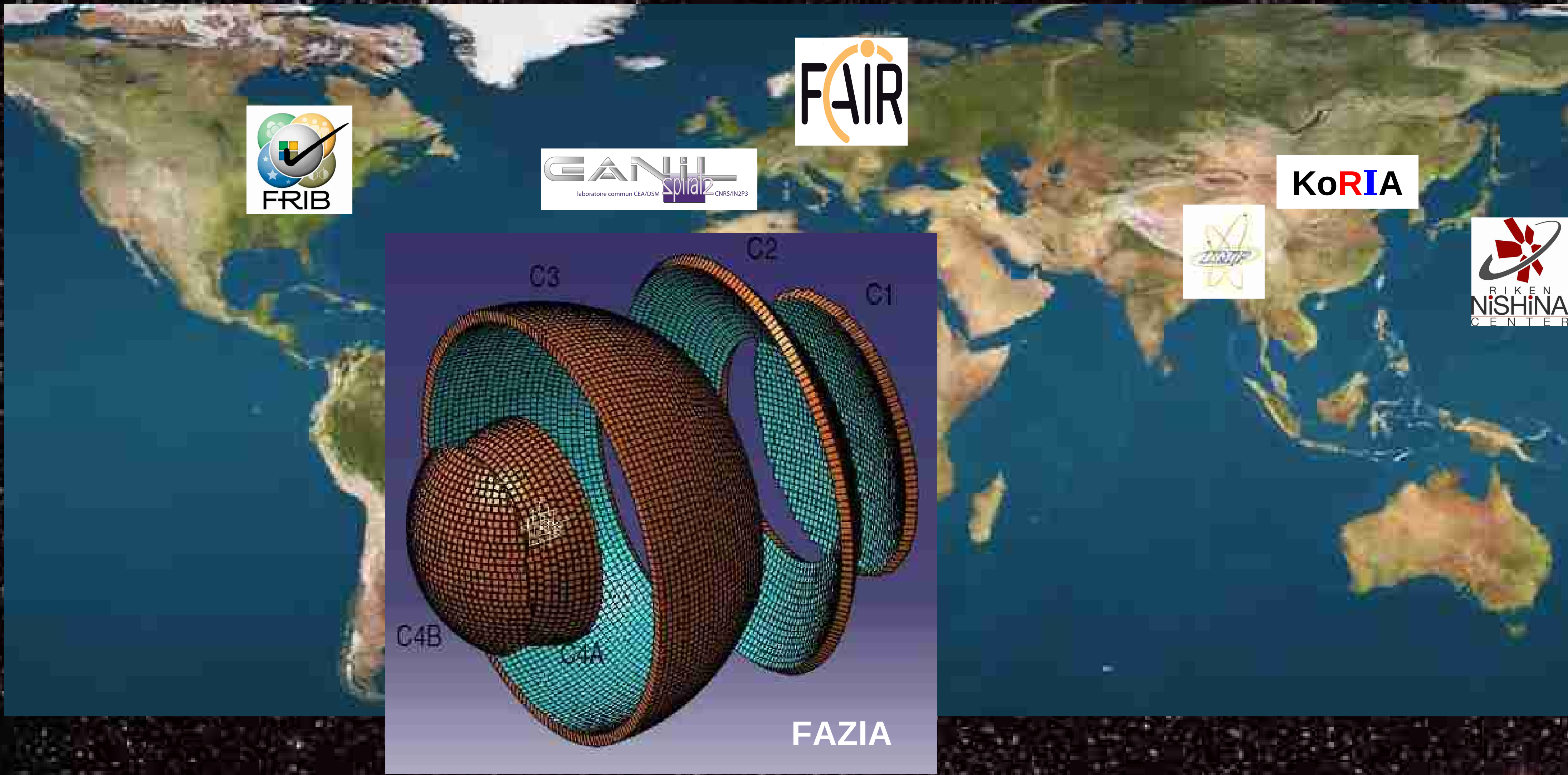




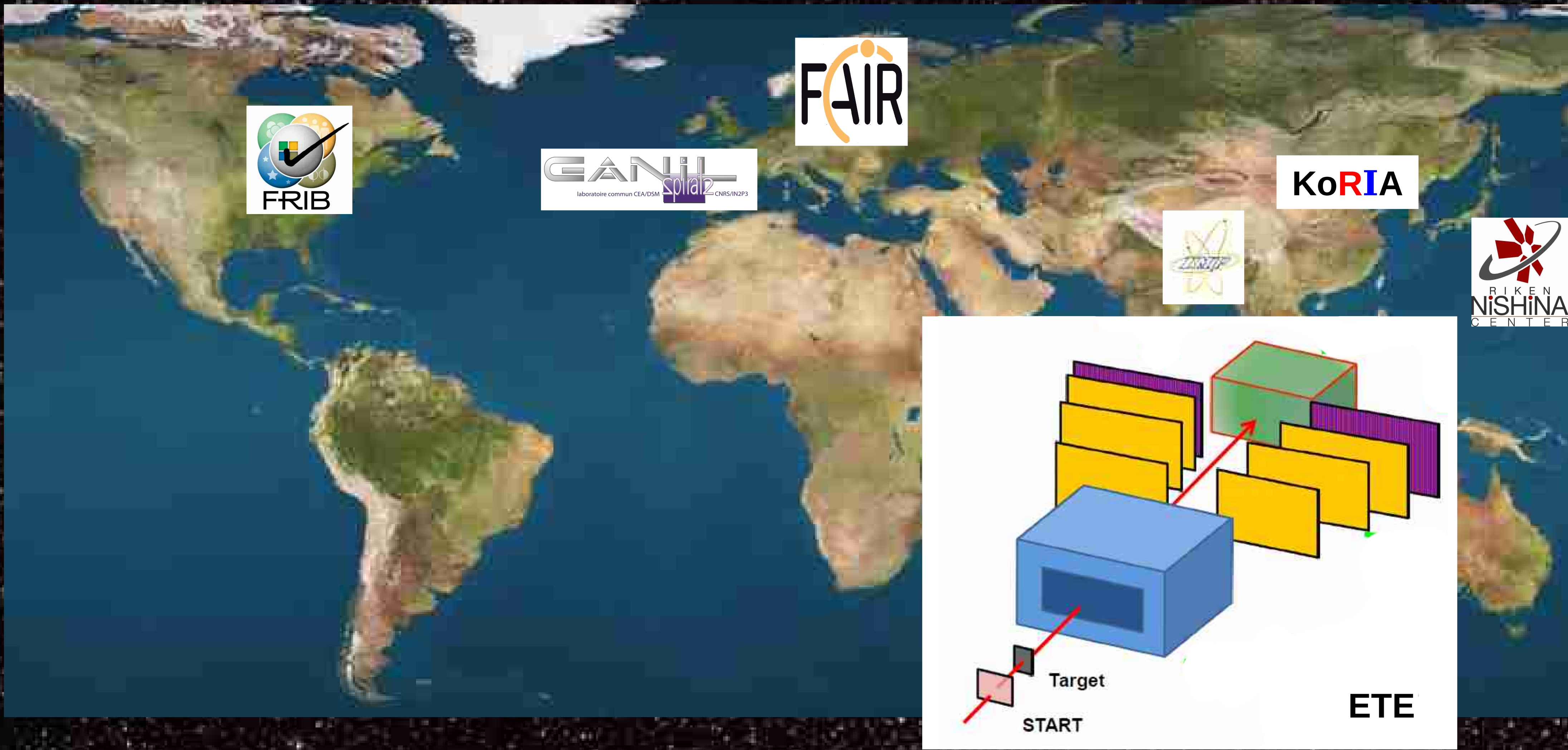
New projects

New projects

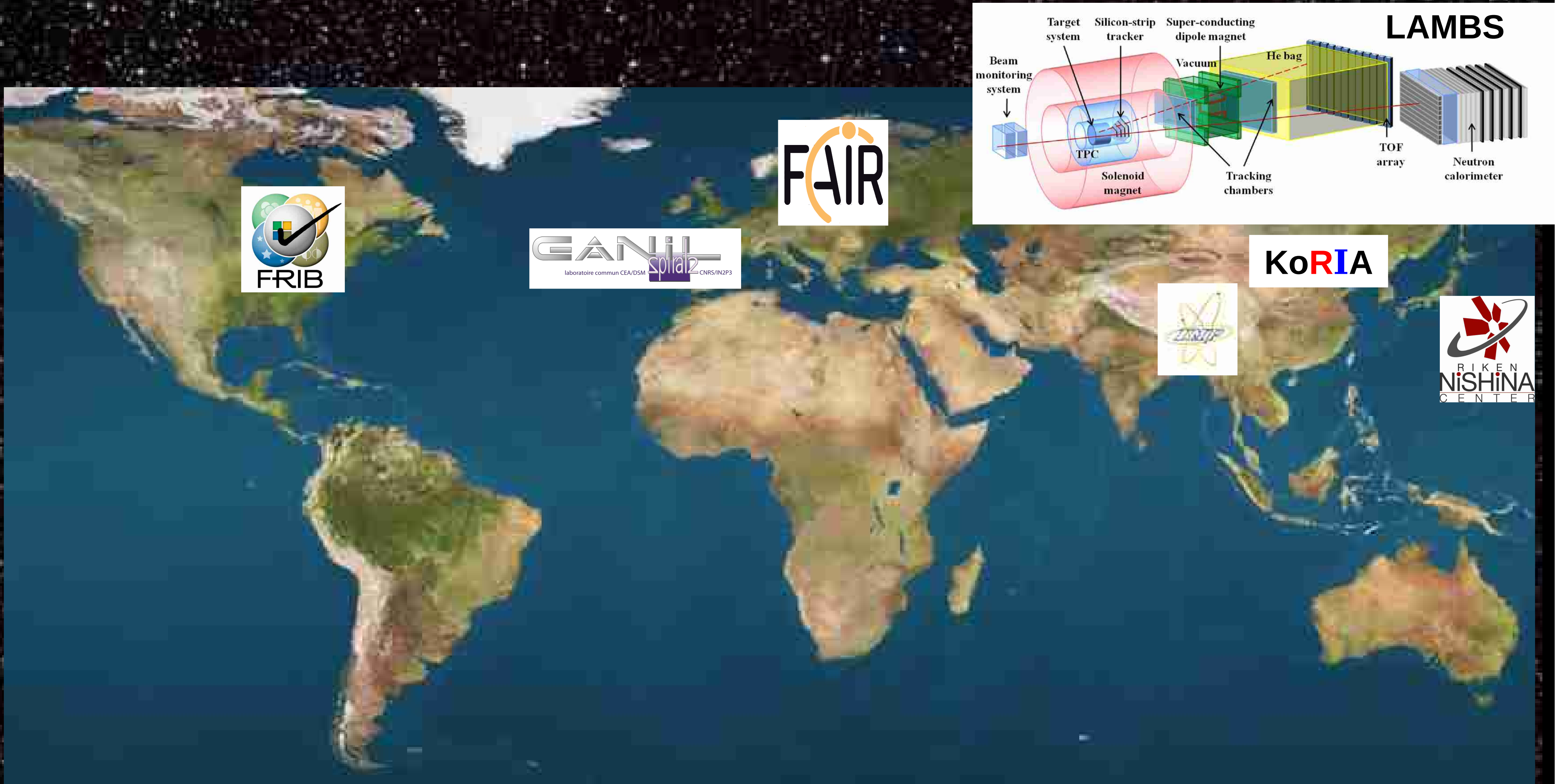
New projects



New projects

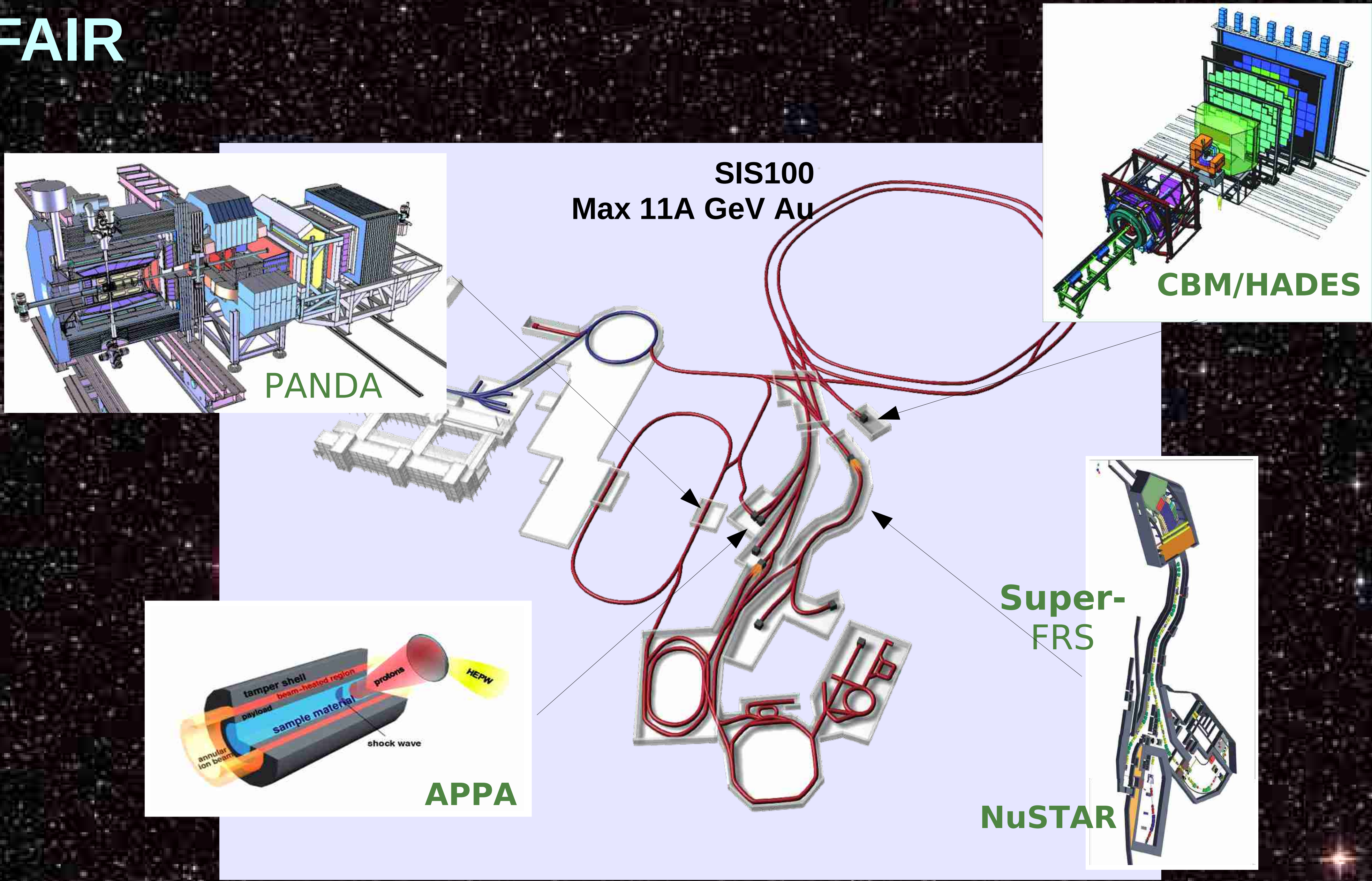


New projects



New projects

FAIR


SIS100
Max 11A GeV Au
PANDA
CBM/HADES
Super-
FRS
NuSTAR
APPA
tamper shell
beam-heated region
payload
sample material
protons
HEPW
shock wave
annular
ion beam

My thanks to the FOPI collaboration

A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, M. Berger, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J. Frühauf, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis, M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija, R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels, A. LeFevre, P. Loizeau, X. Lopez, M. Marquardt, J. Marton, M. Merschmeyer, M. Petrovici, K. Piasecki, F. Rami, V. Ramillien, A. Reischl, W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion, K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski, J. Weinert, K. Wisniewski, Z. Xiao, H.S. Xu, J.T. Yang, I. Yushmanov, V. Zimnyuk, A. Zhilin, Y. Zhang, J. Zmeskal

and

J. Aichelin, E. Bratkovskaya, W. Cassing, C. Hartnack, T.Gaitanos, Q. Li

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ITEP Moscow, Russia
CRIP/KFKI Budapest, Hungary
Kurchatov Institute Moscow, Russia
LPC Clermont-Ferrand, France
Korea University, Seoul, Korea
GSI Darmstadt, Germany
IReS Strasbourg, France
FZ Rossendorf, Germany
Univ. of Heidelberg, Germany
Univ. of Warsaw, Poland
RBI Zagreb, Croatia
IMP Lanzhou, China
SMI Vienna, Austria
TUM, Munich, Germany
+ P. Kienle (TUM), T.Yamazaki(RIKEN)

and to the ASYEOS collaboration

authors of proposal 2009

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and to You


Star clusters young and old
Chris Hetlage
APOD 2006, September 10